

1 **Stratospheric ozone change and related climate**  
2 **impacts over 1850–2100 as modelled by the ACCMIP**  
3 **ensemble**

4  
5 **F. Iglesias-Suarez<sup>1</sup>, P. J. Young<sup>1</sup> and O. Wild<sup>1</sup>**

6 <sup>1</sup>Lancaster Environment Centre, Lancaster University, Lancaster, UK

7 Correspondence to: F. Iglesias-Suarez (n.iglesiassuarez@lancaster.ac.uk)

8

9 **Abstract**

10 Stratospheric ozone and associated climate impacts in the Atmospheric Chemistry and  
11 Climate Model Intercomparison Project (ACCMIP) simulations are evaluated in the  
12 recent past (1980–2000), and examined in the long-term (1850–2100) using the  
13 Representative Concentration Pathways low and high emission scenarios (RCP2.6 and  
14 RCP8.5, respectively) for the period 2000–2100. ACCMIP multi-model mean total  
15 column ozone (TCO) trends compare favourably, within uncertainty estimates,  
16 against observations. Particularly good agreement is seen in the Antarctic austral  
17 spring ( $-11.9\% \text{ dec}^{-1}$  compared to observed  $\sim -13.9 \pm 10.4\% \text{ dec}^{-1}$ ), although larger  
18 deviations are found in the Arctic's boreal spring ( $-2.1\% \text{ dec}^{-1}$  compared to observed  
19  $\sim -5.3 \pm 3.3\% \text{ dec}^{-1}$ ). The simulated ozone hole has cooled the lower stratosphere  
20 during austral spring in the last few decades ( $-2.2 \text{ K dec}^{-1}$ ). This cooling results in  
21 Southern Hemisphere summertime tropospheric circulation changes captured by an  
22 increase in the Southern Annular Mode (SAM) index ( $1.3 \text{ hPa dec}^{-1}$ ). In the future, the  
23 interplay between the ozone hole recovery and greenhouse gases (GHGs)  
24 concentrations may result in the SAM index returning to pre-ozone hole levels or  
25 even with a more positive phase from around the second half of the century ( $-0.4 \text{ hPa}$   
26  $\text{dec}^{-1}$  and  $0.3 \text{ hPa dec}^{-1}$  for the RCP2.6 and RCP8.5, respectively). By 2100,  
27 stratospheric ozone sensitivity to GHG concentrations is greatest in the Arctic and  
28 Northern Hemisphere midlatitudes (37.7 DU and 16.1 DU difference between the  
29 RCP2.6 and RCP8.5, respectively), and smallest over the tropics and Antarctica  
30 continent (2.5 DU and 8.1 DU respectively). Future TCO changes in the tropics are

1 mainly determined by the upper stratospheric ozone sensitivity to GHG  
2 concentrations, due to a large compensation between tropospheric and lower  
3 stratospheric column ozone changes in the two RCP scenarios. These results  
4 demonstrate how changes in stratospheric ozone are tightly linked to climate and  
5 show the benefit of including the processes interactively in climate models.

6

7 **1 Introduction**

8 The Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP)  
9 (Lamarque et al., 2013b) was designed to evaluate the long-term (1850–2100)  
10 atmospheric composition changes (e.g. ozone) to inform the Fifth Assessment Report  
11 of the Intergovernmental Panel on Climate Change (IPCC, 2013), supplementing  
12 phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012),  
13 where the focus was more on physical climate change. In addition, ACCMIP is the  
14 first model intercomparison project in which the majority of the models included  
15 chemical schemes appropriate for stratospheric and tropospheric chemistry. Due to  
16 the absorption of shortwave radiation, stratospheric ozone is important for  
17 determining the stratospheric climate (e.g. Randel and Wu, 1999) and has a strong  
18 influence on tropospheric ozone through stratosphere-to-troposphere transport (e.g.  
19 Collins et al., 2003; Sudo et al., 2003; Zeng and Pyle, 2003). In addition, changes in  
20 stratospheric ozone can affect atmospheric circulation and climate, reaching to the  
21 lower troposphere in the case of the Antarctic ozone hole (e.g. Thompson and  
22 Solomon, 2002; Gillett and Thompson, 2003). This study evaluates stratospheric  
23 ozone changes and associated climate impacts in the ACCMIP simulations,  
24 quantifying the evolution since the pre-industrial period through to the end of the 21<sup>st</sup>  
25 century.

26 Stratospheric ozone represents approximately 90 % of ozone in the atmosphere and  
27 absorbs much of the ultraviolet solar radiation harmful for the biosphere (e.g. WMO,  
28 2014; UNEP, 2015). Anthropogenic emissions of ozone depleting substances (ODS)  
29 such as chlorofluorocarbons and other halogenated compounds containing chlorine  
30 and bromine have played a key role in depleting stratospheric ozone during the latter  
31 half of the 20<sup>th</sup> century (e.g. WMO, 2014). Although present globally averaged TCO  
32 levels are only ~3.5 % lower than pre-1980 values, about half the TCO is depleted

1 over Antarctica between September and November (austral spring) each year (Forster  
2 et al., 2011). Halogen loading peaked around 1998 and started to decrease afterwards  
3 due to the implementation of the Montreal Protocol and its Amendments and  
4 Adjustments (e.g. WMO, 2007, 2014). As a result, stratospheric ozone is expected to  
5 recover and return to pre-industrial values during the 21<sup>st</sup> century (e.g. Austin and  
6 Wilson, 2006; Eyring et al., 2010a). Although anthropogenic ODS are the main cause  
7 of ozone depletion over the last decades, other species such as methane, nitrous  
8 dioxide (N<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>) affect stratospheric ozone chemistry as well  
9 (e.g. Haigh and Pyle, 1982; Portmann et al., 2012; Revell et al., 2012; Reader et al.,  
10 2013). Randeniya et al. (2002) argued that increasing concentrations of methane can  
11 amplify ozone production in the lower stratosphere via photochemical production,  
12 though increases of water vapour from methane oxidation may have the opposite  
13 effect (Dvortsov and Solomon, 2001). Nitrogen oxides (NO<sub>x</sub>) chemistry is important  
14 in the middle-upper stratosphere for ozone; thus, variations and trends in the source  
15 gas (N<sub>2</sub>O) may have a substantial influence on ozone levels (e.g. Ravishankara et al.,  
16 2009; Portmann et al., 2012; Revell et al., 2012).

17 As ODS levels slowly decrease, projected climate change will likely play a key role in  
18 stratospheric ozone evolution through its impacts on temperature and atmospheric  
19 circulation (e.g. IPCC, 2013). The impact of climate change on ozone in the  
20 stratosphere further complicates the attribution of the recovery (e.g. Waugh et al.,  
21 2009a; Eyring et al., 2010b) since increases in CO<sub>2</sub> levels cool the stratosphere,  
22 slowing gas-phase ozone loss processes (e.g. reduced NO<sub>x</sub> abundances; reduced HO<sub>x</sub>-  
23 catalysed ozone loss; and enhanced net oxygen chemistry) resulting in ozone  
24 increases, particularly in the middle-upper stratosphere and high latitudes (e.g. Haigh  
25 and Pyle, 1982; Randeniya et al., 2002; Rosenfield et al., 2002). Further, an  
26 acceleration of the equator-to-pole Brewer-Dobson circulation (BDC) has been  
27 predicted in many model studies under high GHG concentrations (e.g. Butchart et al.,  
28 2006; Garcia and Randel, 2008; Butchart et al., 2010), although its strength can only  
29 be inferred indirectly from observations, meaning that there are large uncertainties in  
30 recent trends (e.g. Engel et al., 2009; Bönisch et al., 2011; Young et al., 2011; Stiller  
31 et al., 2012). This BDC acceleration enhances transport in the atmosphere and  
32 stratospheric-tropospheric exchange (STE), and is likely to have a substantial role  
33 throughout the 21<sup>st</sup> century (e.g. Butchart, 2014). STE is a key transport process that

1 links ozone in the stratosphere and the troposphere (e.g. Holton et al., 1995),  
2 characterised by downward flux of ozone-rich stratospheric air, mainly at mid-  
3 latitudes, and upward transport of ozone-poor tropospheric air in tropical regions. In  
4 contrast, ozone loss cycles could increase with higher N<sub>2</sub>O and lower methane  
5 concentrations (e.g. Randeniya et al., 2002; Ravishankara et al., 2009).

6 Traditionally, chemistry-climate models (CCMs) have been used to produce  
7 stratospheric ozone projections into the past and the future (e.g. WMO, 2007, 2014),  
8 usually prescribing sea surface temperatures and sea-ice concentrations from  
9 observations or climate simulations. Some coordinated climate model experiments,  
10 such as the CMIP5 and the Chemistry-Climate Model Validation activities (CCMVal  
11 and CCMVal2) (Eyring et al., 2006; Eyring et al., 2007; Austin et al., 2010; Eyring et  
12 al., 2010a; Eyring et al., 2013) have examined stratospheric ozone evolution. Recent  
13 past stratospheric column ozone projections (~1960–2000), from the above  
14 coordinated climate model experiments, show substantial decreases driven mainly by  
15 anthropogenic emissions of ODS and agree well with observations. However, future  
16 stratospheric ozone projections are influenced by both the slow decrease in ODS  
17 levels and the climate scenario chosen. To illustrate this, Eyring et al. (2013) used a  
18 subgroup of CMIP5 models with interactive chemistry in the stratosphere and the  
19 troposphere to show gradual recovery of ozone levels during the next decades (as  
20 ODS abundances decrease in the stratosphere), and global multi-model mean  
21 stratospheric column ozone “super-recovery” (higher levels than those projected in  
22 the pre-ozone depletion period) for the most pessimistic emission scenario (RCP8.5)  
23 at the end of the 21<sup>st</sup> century. A main recommendation from the SPARC-CCMVal  
24 (2010) report is that CCMs should keep developing towards self-consistent  
25 stratosphere-troposphere chemistry, interactively coupled to the dynamics and  
26 radiation (e.g. enabling chemistry-climate feedbacks).

27 Tropospheric ozone accounts for the remaining ~10 % atmospheric ozone, where it is  
28 a GHG, a pollutant with significant negative effects to vegetation and human health,  
29 and a main source of hydroxyl radicals controlling the oxidising capacity of the  
30 atmosphere (e.g. Prather et al. 2001; Gregg et al., 2003; Jerrett et al., 2009). Its  
31 abundance in the troposphere is determined from the balance of STE and  
32 photochemistry production involving the oxidation of hydrocarbons and carbon  
33 monoxide (CO) in the presence of NO<sub>x</sub>, versus chemical destruction and deposition to

1 the surface (e.g. Lelieveld and Dentener, 2000; Wild, 2007). These terms depend in  
2 turn on climate system dynamics (e.g. STE) and on the magnitude and spatial  
3 distribution of ozone precursors emissions such as, volatile organic compounds, NO<sub>x</sub>  
4 and CO (e.g. chemical production and destruction) (e.g. Wild, 2007). Several studies  
5 found tropospheric ozone increases due to climate change via enhanced STE (e.g.  
6 Collins et al., 2003; Sudo et al., 2003; Zeng and Pyle, 2003). Other studies have  
7 shown positive relationship between anthropogenic emissions and tropospheric ozone  
8 abundance (e.g. Stevenson et al., 2006; Young et al., 2013a). However, the ultimately  
9 net impact of climate and emissions changes remains unclear (Stevenson et al., 2006;  
10 Isaksen et al., 2009; Jacob and Winner, 2009), and it may differ substantially by  
11 region, altitude or season (e.g. Myhre et al., 2013).

12 Further, the ozone hole influences surface climate via temperature and circulation  
13 changes (e.g. Thompson and Solomon, 2002; Gillett and Thompson, 2003) owing to  
14 direct radiative effects (e.g. Randel and Wu, 1999; Forster et al., 2011). The ozone  
15 layer heats the stratosphere by absorbing incoming ultraviolet solar radiation, hence,  
16 trends and variations on ozone would impact stratospheric dynamics (e.g.  
17 Ramaswamy et al., 2006; Randel et al., 2009; Gillett et al., 2011). In the Southern  
18 Hemisphere (SH), stratospheric circulation changes associated to ozone depletion  
19 have been linked to tropospheric circulation changes primarily during austral summer  
20 (lagging the former 1-2 months), based on observations (Thompson and Solomon,  
21 2002) and model simulations (Gillett and Thompson, 2003). These SH extratropical  
22 circulation changes could be described by the leading mode of variability or the SAM  
23 (e.g. Thompson and Wallace, 2000). Previous studies based on CCMs simulations  
24 reported positive trends in the SAM over the ozone depletion period (e.g. Sexton,  
25 2001; Shindell and Schmidt, 2004; Arblaster and Meehl, 2006; Polvani et al., 2010;  
26 McLandress et al., 2011). Furthermore, some modelling studies have projected a  
27 poleward shift (i.e. positive change) in the SAM due to future increases in GHGs (e.g.  
28 Fyfe et al., 1999; Marshall et al., 2004). Projected ozone recovery should have the  
29 opposite effect than ozone depletion (i.e. a negative trend in the SAM), and this is  
30 important as it opposes the effect of increasing GHG concentrations. Some studies  
31 suggest that these effects will largely cancel out each other during the next several  
32 decades in austral summer owing to these competing forces (e.g. Perlwitz et al., 2008;

1 Son et al., 2009; Arblaster et al., 2011; Polvani et al., 2011; Barnes et al., 2013; Gillett  
2 and Fyfe, 2013).

3 Multi-model experiments are useful for evaluating model differences in not fully  
4 understood processes and associated feedbacks, and for identifying agreements and  
5 disagreements between various parameterisations (e.g. Shindell et al., 2006;  
6 Stevenson et al., 2006). While CMIP5 provides a framework towards a more Earth  
7 System approach to intercompare model simulations and enables their improvement,  
8 it lacks comprehensive information on atmospheric composition and models with full  
9 interactive chemistry (Lamarque et al., 2013b). ACCMIP aims to fill this gap by  
10 evaluating how atmospheric composition drives climate change, and provides a gauge  
11 of the uncertainty by different physical and chemical parameterisations in models  
12 (Myhre et al., 2013). In this study we quantify the evolution of stratospheric ozone  
13 and related climate impacts in the ACCMIP simulations from pre-industrial times  
14 (1850), recent past (1980) and present day (2000) to the near-future (2030) and the  
15 end of the 21<sup>st</sup> century (2100). First, we evaluate recent past and present-day  
16 ACCMIP stratospheric ozone simulations with observations and other model based  
17 products. Then, we assess ozone projections and ozone sensitivity to GHG  
18 concentrations. Finally, a description of the associated impacts of stratospheric ozone  
19 depletion and projected recovery in the climate system is presented, with a focus in  
20 the SH. In addition, this study compares ACCMIP simulations with those from  
21 CMIP5 and CCMVal2 and identifies agreements and disagreements among different  
22 parameterisations. This paper complements previous analysis of the ACCMIP  
23 simulations on tropospheric ozone evolution (Young et al., 2013a; Parrish et al.,  
24 2014), radiative forcing (Bowman et al., 2013; Shindell et al., 2013a; Stevenson et al.,  
25 2013), hydroxyl radical and methane lifetime (Naik et al., 2013b; Voulgarakis et al.,  
26 2013), historical black carbon evaluation (Lee et al., 2013), nitrogen and sulfur  
27 deposition (Lamarque et al., 2013a), and climate evaluation (Lamarque et al., 2013b).

28 The remainder of this paper is organised as follows. Section 2 describes the models  
29 and simulations used here, with a focus on the various ozone chemistry schemes. In  
30 Section 3, ozone is examined in the recent past against observations, and analysed  
31 from 1850 to 2100 under the low and high RCPs emission scenarios for those models  
32 with interactive chemistry-climate feedback. Section 4 explores past and future  
33 stratospheric ozone evolution and climate interactions. A discussion of the results is

1 presented in Section 5, followed by a brief summary and main conclusions in Section  
2 6.

3

## 4 **2 Models, simulations and analysis**

5 In this section we describe main details of the ACCMIP models, simulations, and  
6 analyses conducted in this paper. A comprehensive description of the models and  
7 simulations along with further references are provided by Lamarque et al. (2013b).

### 8 **2.1 ACCMIP models**

9 Table 1 summarises the ACCMIP models analysed in this study and their important  
10 features. We considered 8 models that had time-varying stratospheric ozone, either  
11 prescribed (offline) or interactively calculated (online). From the full ACCMIP  
12 ensemble (Lamarque et al., 2013b), we have excluded: EMAC, GEOSCCM and  
13 GISS-E2-TOMAS, as these did not produce output for all the scenarios and time  
14 periods analysed here (see Section 2.2); CICERO-OsloCTM and LMDzORINCA, as  
15 these used a constant climatological value of stratospheric ozone; MOCAGE and  
16 STOC-HadAM3, which showed poor stratospheric ozone chemistry performance  
17 compared to observations; and NCAR-CAM5.1, as this model was focused on aerosol  
18 output and did not save ozone fields.

19 The ACCMIP models included in this study are CCMs (7) or chemistry general  
20 circulation models (1) with atmospheric chemistry modules. The CCMs implemented  
21 a coupled composition-radiation scheme, whereas the chemistry and radiation was not  
22 coupled in UM-CAM (see Table 1). Both sea surface temperatures and sea-ice  
23 concentrations were prescribed, except in GISS-E2-R which interactively calculated  
24 them. Similarly to Eyring et al. (2013), we group the models into two categories: 6  
25 models with full atmospheric chemistry (CHEM), and 2 models with online  
26 tropospheric chemistry but with prescribed ozone in the stratosphere (NOCHEM)  
27 (Figure 4 of Lamarque et al., 2013b). All CHEM models included ODS (with Cl and  
28 Br) and the impact of polar stratospheric clouds (PSCs) on heterogeneous chemistry,  
29 although a linearised ozone chemistry parameterisation was implemented in CESM-  
30 CAM-Superfast (McLinden et al., 2000; Hsu and Prather, 2009). The other two

1 models, HadGEM2 and UM-CAM, prescribed stratospheric ozone concentrations  
2 from the IGAC/SPARC database (Cionni et al., 2011).

3 A final important distinction among the models is how stratospheric changes are able  
4 to influence photolysis rates. The simplest scheme is for HadGEM2 and UM-CAM,  
5 where the photolysis rates are derived from a look-up table as a function of time,  
6 latitude and altitude only, and using a climatological cloud and ozone fields (i.e. the  
7 rates are the same for all simulations) (e.g. Zeng et al., 2008; Zeng et al., 2010;  
8 Collins et al., 2011; Martin et al., 2011). The look-up table is more complex with  
9 CESM-CAM-Superfast (Gent et al., 2010), CMAM (Scinocca et al., 2008), GFDL-  
10 AM3 (Donner et al., 2011; Griffies et al., 2011) and NCAR-CAM3.5 (Gent et al.,  
11 2010; Lamarque et al., 2012), where an adjustment is applied to take surface albedo  
12 and cloudiness into account, which couples with the simulated aerosols. Fully online  
13 photolysis calculations were only made for MIROC-CHEM (Watanabe et al., 2011)  
14 and GISS-E2-R (Schmidt et al., 2006; Shindell et al., 2013b).

15 As per Young et al. (2013a), all models were interpolated to a common grid (5° by 5°  
16 latitude/longitude and 24 pressure levels).

## 17 **2.2 ACCMIP scenarios and simulations**

18 The ACCMIP simulations were designed to span the pre-industrial period to the end  
19 of the 21<sup>st</sup> century. In this study, time slices from the years 1850, 1980 and 2000  
20 comprise historical projections (hereafter Hist), whereas time slices from the years  
21 2030 and 2100 future simulations. The latter follow the climate and  
22 composition/emission projections prescribed by the Representative Concentration  
23 Pathways (RCPs) (van Vuuren et al., 2011; Lamarque et al., 2012), named after their  
24 nominal radiative forcing at the end of the 21<sup>st</sup> century relative to 1750. Here we  
25 consider RCP2.6 (referring to 2.6 Wm<sup>-2</sup>) and RCP8.5 (8.5 Wm<sup>-2</sup>), since they bracket  
26 the range of warming in the ACCMIP simulations, and are the scenarios that have  
27 been completed by the greatest number of models.

28 Future ODS (the total organic chlorine and bromine compounds) in CHEM models  
29 follow the RCPs values from Meinshausen et al. (2011), which does not include the  
30 early phase-out of hydrochlorofluorocarbons agreed in 2007 by the Parties to the  
31 Montreal Protocol. Note that ODS may be specified as concentrations (CMAM,  
32 GFDL-AM3 and NCAR-CAM3.5) or emissions (CESM-CAM-superfast, GISS-E2-R,

1 MIROC-CHEM) in different models, though these were the same within each time  
2 slice simulation (except for GISS-E2-R; see below). No significant trends are found  
3 for stratospheric ozone in those years that form part of the Hist 1980 time slice for the  
4 latter models, even though ODS were specified as emissions (i.e. any trends in ODS  
5 concentration in the stratosphere due to transport timescales do not significantly affect  
6 ozone concentrations). This is slightly different from the modified halogen scenario of  
7 WMO (2007) used in the IGAC/SPARC ozone database employed by the NOCHEM  
8 models. Nevertheless, halogen concentrations in both future scenarios peak around the  
9 year 2000 and decline afterwards, although slightly different timing of ozone  
10 returning to historical levels may be found. Tropospheric ozone precursors emissions  
11 follow Lamarque et al. (2010) for the historical period, and Lamarque et al. (2013b)  
12 for the RCPs.

13 Most models completed time slice simulations for each period and scenario, usually  
14 10 years average about each time slice (e.g. 1975–1984 for the Hist 1980 time slice,  
15 although other models simulated time slices ranging from 5 to 11 years). Notice that  
16 interannual variability for a given time slice is generally small (Young et al., 2013a).  
17 The exception is GISS-E2-R, which ran transient simulations with a coupled ocean.  
18 Equivalent time slice means were calculated by averaging 10 years centred on the  
19 desired time slice, (1975–1984 for 1980 and so forth), except for the 1850 time slice  
20 (1850–1859 mean).

### 21 **2.3 CMIP5 and CCMVal2 simulations**

22 We also include CMIP5 and CCMVal2 simulations as a benchmark for the former  
23 models. We use a subset of five “high” top CMIP5 models, defined here as those  
24 models that represented and saved ozone output above 10 hPa for the historical  
25 (1850–2005, most of the models), and future (RCP2.6 and RCP8.5, 2005–2100)  
26 emission scenarios: CESM1-WACCM, GFDL-CM3, MPI-ESM-LR, MIROC-ESM,  
27 and MIROC-ESM-CHEM. Only high top models are considered here due to the  
28 implications the upper stratosphere has on, among other factors, stratospheric  
29 dynamical variability (Charlton-Perez et al., 2013), and tropospheric circulation  
30 (Wilcox et al., 2012). Moreover, we will show how, in the tropics, upper stratospheric  
31 ozone plays a key role on TCO projections during the 21<sup>st</sup> century (see Section 3.2).  
32 Again, we group the models into two categories: 3 models with full atmospheric

1 chemistry (CHEM: CESM1-WACCM, GFDL-CM3 and MIROC-ESM-CHEM), and  
2 2 models with prescribed ozone (NOCHEM: MPI-ESM-LR and MIROC-ESM). A  
3 detailed description of the models, simulations and ozone concentrations are  
4 presented by Taylor et al. (2012) and Eyring et al. (2013).

5 In addition, we include 14 CCMVal2 models that represented ozone under the REF-  
6 B1 scenario (1960–2006, most of the models): CAM3.5, CCSRNIES, CMAM,  
7 E39CA, EMAC, GEOSCCM, LMDZrepro, Niwa-SOCOL, SOCOL, ULAQ,  
8 UMETRAC, UМУKCA-METO, UМУKCA-UCAM and WACCM. All these models  
9 had interactive stratospheric chemistry and coupled composition-climate feedback,  
10 although simplified or absent chemistry in the troposphere. Morgenstern et al. (2010b)  
11 describe in detail CCMVal2 models and REF-B1 simulations.

12 In contrast to ACCMIP time slice simulations, these data sets were based on transient  
13 experiments, which may result in slightly different ozone levels, as simulations depart  
14 from initial conditions. Nevertheless, equivalent time slice means were calculated in  
15 the same manner as above for consistency purposes throughout all analysis involving  
16 trends or ozone changes. Note, however, that calculating trends using least-squares  
17 linear fits from their transient runs would not have a significant impact on the results.  
18 A caveat is that TCO was calculated from the ozone mixing ratio field, which may  
19 slightly differ (~1.5 %) from that of the model’s native TCO (Eyring et al., 2013).

## 20 **2.4 Tropopause definition**

21 For the purpose of comparing the outputs among models, a tracer tropopause  
22 definition has been argued to be suitable (Wild, 2007). This study follows Young et  
23 al. (2013a) method, in which the tropopause is based on the 150 ppbv ozone contour,  
24 after Prather et al. (2001). The definition is fitted for all time slices using ozone from  
25 the Hist 1850 time slice for each model and month; meaning that the “troposphere” is  
26 defined as a fixed volume region of the atmosphere. On the one hand, Young et al.  
27 (2013a) argued that using a monthly mean tropopause from the 1850 time slice  
28 prevents issues with different degrees of ozone depletion among the models,  
29 especially for SH high latitudes. On the other hand, this neglects the fact that the  
30 tropopause height may vary with time due to climate change (e.g. Santer et al., 2003a;  
31 Santer et al., 2003b). Nevertheless, Young et al. (2013a) have shown that using ozone

1 from the Hist 2000 time slice to define the tropopause across all time slices, generally  
2 results in tropospheric ozone columns of  $\pm 5\%$  compared to the Hist 1850 time slice.

3

### 4 **3 Long-term total column ozone evolution in the ACCMIP models**

5 This section presents an evaluation of the present-day (Hist 2000) TCO distribution  
6 and recent (1980–2000) ozone trends against observations and observationally-  
7 derived data. The evolution of TCO from the pre-industrial period (1850) to the end  
8 of the 21<sup>st</sup> century (2100) is also discussed, with a particular focus on the different  
9 contribution of trends in the tropical tropospheric, lower stratospheric, and upper  
10 stratospheric columns to the total column trend. Previously, Young et al. (2013a) have  
11 shown that TCO distribution changes in the ACCMIP multi-model mean agree well  
12 with the Total Ozone Mapping Spectrometer (TOMS) for the last few decades (their  
13 Fig. S7). However, ACCMIP models simulate weaker (not significant) ozone  
14 depletion in early boreal spring over the Arctic between Hist 1980 and 2000  
15 compared to TOMS (see also Sections 3.1 and 5).

#### 16 **3.1 Evaluation of ozone trends, 1980–2000**

17 Figure 1 shows TCO decadal trends between 1980 and 2000 for the global mean, and  
18 a number of latitude bands. The figure compares the ACCMIP, CMIP5 and CCMVal2  
19 models against the Bodeker Scientific TCO data set (BodSci TCO - version 2.8),  
20 combining a number of different satellite-based instruments (Bodeker et al., 2005;  
21 Struthers et al., 2009), and observations from the Solar Backscatter Ultraviolet  
22 (SBUV - version 8.6) merged ozone data sets (McPeters et al., 2013). In addition,  
23 Figure 1 includes trends from the IGAC/SPARC ozone data set (Cionni et al., 2011)  
24 which was used by the majority of the models with prescribed ozone concentrations  
25 (both ACCMIP and CMIP5). The different data sets trends are broadly comparable  
26 but differ slightly in their calculation and uncertainty determination. For ACCMIP,  
27 CMIP5 and CCMVal2 models, the trends are for the differences between the Hist  
28 1980 and 2000 time slices with the range shown as box/whisker plots (central 50 % of  
29 trends as the box; 95 % confidence intervals as the whiskers). Trends for the  
30 observations and IGAC/SPARC database are linear trends with error bars indicating  
31 the 95 % confidence level based on the standard error for the fit, and corrected for

1 lag-1 autocorrelation for the former (Santer et al., 2000). The annual mean is used in  
2 evaluations for the global, tropical and midlatitudes regions. Additional evaluations  
3 are made for the boreal spring in the Arctic (March, April and May) and the austral  
4 spring in the Antarctic (September, October and November) when strongest ozone  
5 depletion occurs.

6 Within uncertainty, the overall response for ACCMIP is in good agreement with  
7 observational data sets in terms of decadal trends and absolute values, with the  
8 Northern Hemisphere (NH) being the region where models differ most. In line with  
9 CMIP5 and CCMVal2 models, strongest changes are found over Antarctica in austral  
10 spring associated to the ozone hole, and smallest over the tropics where ODS are least  
11 effective. ACCMIP NOCHEM models typically simulate smaller decadal trends than  
12 CHEM models, consistent with the possible underestimation of SH ozone depletion  
13 trends in the IGAC/SPARC ozone data set (Hassler et al., 2013; Young et al., 2014).  
14 However, outside extratropical SH regions, IGAC/SPARC ozone data set (i.e. used to  
15 drive the majority of ACCMIP and CMIP5 NOCHEM models) tends to show better  
16 agreement with observations than CHEM models. ACCMIP CHEM and CMIP5  
17 CHEM models show very similar TCO decadal trends in all regions ( $\pm 0.1\text{--}0.2\% \text{ dec}^{-1}$ )  
18 <sup>1</sup>), although differing somewhat more at high latitudes in the SH, where ozone  
19 depletion is greatest ( $\pm 2.9\% \text{ dec}^{-1}$ ). ACCMIP NOCHEM and CMIP5 NOCHEM  
20 models show more disparate trends ( $\pm 0.5\text{--}2.1\% \text{ dec}^{-1}$ ), which may be related to  
21 different ozone data sets and the implementation method on each model (i.e. online  
22 tropospheric chemistry in ACCMIP models).

23 Figure 2 compares vertically resolved ozone decadal trends for the same period,  
24 regions and seasons, for the ACCMIP multi-model mean and individual models  
25 against the Binary Database of Profiles (BDBP version 1.1.0.6) data set, using the so-  
26 called Tier 0 and Tier 1.4 data (Bodeker et al., 2013). Tier 0 includes ozone  
27 measurements from a wide range of satellite and ground-based platforms, whereas  
28 Tier 1.4 is a regression model fitted to the same observations. Uncertainty estimates  
29 for the BDBP Tier 1.4 trends are from the linear least square fits, as for the  
30 observations in Figure 1. ACCMIP shows most disagreement with the BDBP data in  
31 the lower and middle stratosphere region and best agreement with Tier 1.4 in the  
32 upper stratosphere.

1 In the Tropics (Figure 1b), TCO in all data sets agrees fairly well with observations.  
2 Although ACCMIP, CMIP5 and CCMVal2 simulate small decadal trends ( $-0.4$ ,  $-0.7$   
3 and  $-0.9$  % dec<sup>-1</sup> respectively), the spread of the models at the 95 % confidence  
4 interval stays within the negative range. However, uncertainty estimates in TCO in the  
5 SBUV and BodSci TCO data sets embrace trends of different sign ( $-0.7 \pm 1.5$  % dec<sup>-1</sup>  
6 <sup>1</sup>, and  $-0.4 \pm 2.3$  % dec<sup>-1</sup> respectively). IGAC/SPARC presents slightly larger  
7 negative decadal trends than observations in this region. CMIP5 CHEM and  
8 CCMVal2 multi-model means show slightly stronger decadal trends than ACCMIP  
9 CHEM models in this region. In terms of absolute values, the spread of the ACCMIP  
10 models overlaps the observed TCO for the Hist 2000 time slice, though most models  
11 differ by more than the observational standard deviation (7 out of 8). Biases in TCO  
12 may be attributed to different altitude regions (Figure 2b). ACCMIP models fail to  
13 represent observed ozone depletion occurring in the lower and middle stratosphere  
14 region, which may be linked to a poor representation of the HO<sub>x</sub> and upwelling in this  
15 region (e.g. Lary, 1997; Randel et al., 2007).

16 In the NH midlatitudes (Figure 1c), TCO trends in ACCMIP and CMIP5 CHEM  
17 models ( $-0.8$  and  $-0.9$  % dec<sup>-1</sup> respectively) underestimate larger negative trends than  
18 observation estimates ( $-2.3 \pm 1.2$  % dec<sup>-1</sup>), though the CCMVal2 multi-model mean  
19 ( $-1.4$  % dec<sup>-1</sup>) is within the observational uncertainty. TCO decadal trends for  
20 IGAC/SPARC and NOCHEM models show better agreement with observations than  
21 CHEM models in this region. Due to the BDC, the abundance of ozone at  
22 midlatitudes is affected by the relatively ozone-rich air coming from the upper  
23 stratosphere over the tropics. The ACCMIP Hist 2000 simulation agrees fairly well  
24 with observations in terms of absolute values, however, once again most models  
25 diverge by more than the observational standard deviation (7 out of 8). The ACCMIP  
26 multi-model mean falls within the BDBP Tier 1.4 uncertainty estimates for most of  
27 the lowermost and middle stratosphere, though simulates weaker ozone depletion in  
28 the lower stratosphere, which may be associated with the weaker than observed ozone  
29 depletion over the Arctic (Figure 2c).

30 Over the Arctic in boreal spring (Figure 1e), again the ACCMIP CHEM, CMIP5  
31 CHEM and CCMVal2 data sets show weaker decadal trends than observations ( $-2.1$ ,  
32  $-2.3$  and  $-2.5$  % dec<sup>-1</sup> respectively compared to  $-5.3 \pm 3.3$  % dec<sup>-1</sup>). However, TCO  
33 for Hist 2000 in ACCMIP is in good agreement with observations, with no individual

1 model differing by more than the observational standard deviation. In the altitude  
2 region around 150–30 hPa, the ACCMIP multi-model mean is underestimating larger  
3 negative trends compared to the BDBP data (Figure 2e).

4 In the SH midlatitudes (Figure 1d), ACCMIP simulates TCO decadal trends in better  
5 agreement with observations than in the NH midlatitudes ( $-2.0 \text{ \% dec}^{-1}$  compared to  
6  $-2.9 \pm 1.3 \text{ \% dec}^{-1}$ ), except for the ACCMIP NOCHEM mean which is significantly  
7 underestimating larger negative trends ( $-1.1 \text{ \% dec}^{-1}$ ). In terms of absolute values in  
8 present-day conditions, most ACCMIP models' TCO is either high or low biased  
9 compared to observations (7 out of 8). The ACCMIP multi-model mean is again  
10 underestimating larger negative trends compared to the BDBP data set in the altitude  
11 range between 150–30 hPa (notice that Tier 1.4 trends are more uncertain in this  
12 region), which may be associated to the influence of the tropics and in-situ  $\text{HO}_x$   
13 catalytic loss cycle (e.g. Lary, 1997) (Figure 2d).

14 Over Antarctica in austral spring (Figure 1f), ACCMIP CHEM and CMIP5 multi-  
15 model means show best agreement compared to observations ( $-12.9 \text{ \% dec}^{-1}$  and  
16  $-13.9 \text{ \% dec}^{-1}$  respectively compared to  $\sim -13.9 \pm 10.4 \text{ \% dec}^{-1}$ ), although all data sets  
17 fall within observational uncertainty estimates. IGAC/SPARC ozone data set and  
18 NOCHEM models simulate less ozone depletion in this region ( $-11.4 \text{ \% dec}^{-1}$  and  
19  $-8.8 \text{ \% dec}^{-1}$  respectively) than models with interactive chemistry. Although, many  
20 ACCMIP models are in good agreement with observations in terms of absolute values  
21 for the Hist 2000 time slice, one CHEM model deviates more than the observational  
22 standard deviation. ACCMIP models show fairly good agreement with BDBP Tier 1.4  
23 decadal trends at various altitude regions, except around 70–30 hPa, which is also the  
24 region where the modelled temperature trends are more negative than observed (see  
25 Section 5). This is consistent with previous analyses which suggested that models  
26 potentially simulate too strong negative trend for a given ozone depletion (e.g. Young  
27 et al., 2011) and this discrepancy warrants further investigation in future model  
28 intercomparison studies, where there is more model output available.

### 29 **3.2 Past modelled and future projected total column ozone**

30 In this section, the evolution of past modelled TCO (from 1850 to 2000) and the  
31 sensitivity of ozone to future GHG emissions (from 2030 to 2100) under the lower  
32 and higher RCPs scenarios are discussed for the regions and seasons presented in the

1 evaluation section. In the tropical region, TCO evolution is further analysed by  
2 looking at the stratospheric (split into upper and lower regions) and tropospheric  
3 columns ozone. Historical and future global annual mean of TCO and associated  
4 uncertainty ( $\pm 1$  standard deviation) for the ACCMIP and CMIP5 CHEM models and  
5 the IGAC/SPARC data set is given in Table 2.

6 To probe how different emissions of GHG affect stratospheric ozone, we only include  
7 in this section ACCMIP and CMIP5 models with full ozone chemistry (CHEM). In  
8 addition, we compare these results with the IGAC/SPARC database, generally used  
9 by those models with prescribed stratospheric ozone. Note that tropospheric column  
10 ozone under the RCPs at the end of the 21<sup>st</sup> century could lead to differences in TCO  
11 around 20 DU, due to differences in ozone precursors emissions (e.g. methane)  
12 (Young et al., 2013a). Again, vertical resolved ozone changes are presented to give  
13 insight on the vertical distribution of ozone changes (for the 1850–2100 and  
14 2000–2100 periods).

15 Figure 3 shows, except for the extratropical regions in the SH, an increase in TCO  
16 from the pre-industrial period (Hist 1850) to the near-past (Hist 1980) owing to ozone  
17 precursors emissions. In the SH extratropical, due to special conditions (e.g. greater  
18 isolation from the main sources of ozone precursors and stratospheric cold  
19 temperatures during austral winter and early spring), there is a decrease in TCO that is  
20 particularly pronounced over Antarctica ( $-12.4\%$ ). Between near-past and present-  
21 day (Hist 2000), a period characterised by ODS emissions, the TCO decreases  
22 everywhere, with the magnitude being dependent on the region. Thus, the relative  
23 change of TCO between the present-day and pre-industrial periods varies across  
24 different regions, mainly due to the competing effects of ozone precursors and ODS  
25 emissions (approximately, from  $2.9\%$  in the NH midlatitudes and  $-34.9\%$  over  
26 Antarctica). Notice, however, that minimal stratospheric ozone depletion occurs  
27 before the 1960s.

28 Future TCO projected for the RCPs 2100 time slices relative to present-day are  
29 affected by the impact of the Montreal Protocol on limiting ODS emissions, climate  
30 change and ozone precursors emissions. TCO changes between 2000 and 2100  
31 relative to the pre-industrial period for the low and high emission scenarios are in the  
32 range of approximately from  $-1.2\%$  to  $2.0\%$  in the tropics and  $28.3\text{--}31.7\%$  over  
33 Antarctica, respectively. Ozone “super-recovery”, defined here as higher stratospheric

1 ozone levels than those during pre-ozone depletion (1850), is found for ACCMIP  
2 CHEM models in RCP8.5 2100 in all regions and seasons, with the exception in the  
3 tropics and over Antarctica during austral spring. As expected from the above climate  
4 impacts, the biggest super-recovery is found, in the order of 12.6 % over the Arctic  
5 during boreal spring, and between 3.9–6.5 % at midlatitudes for the RCP8.5 2100  
6 time slice. Similar levels of stratospheric ozone super-recovery are found in the  
7 CMIP5 CHEM models. In contrast, the IGAC/SPARC database only projects small  
8 super-recovery in the NH polar region and at midlatitudes in the SH. These ozone  
9 super-recovery results are consistent with recent findings on stratospheric ozone  
10 sensitivity to GHG concentrations (Waugh et al., 2009a; Eyring et al., 2010b).

11 We give special attention to TCO projections in the tropics, since an acceleration  
12 of the BDC, due to increases in GHG concentrations would lead to a rise of  
13 tropospheric ozone-poor air entering the tropical lower stratosphere (Butchart  
14 et al., 2006; Butchart et al., 2010; SPARC-CCMVal, 2010; Butchart et al., 2011;  
15 Eyring et al., 2013). In other words, ozone concentrations in the lower  
16 stratosphere would decrease with high GHG emissions.

17 Figure 4 presents upper (10-1 hPa) and lower (>15 hPa) stratospheric and  
18 tropospheric columns ozone in the tropics, from the pre-industrial period to the  
19 end of the 21<sup>st</sup> century. Tropospheric column ozone increases with higher ozone  
20 precursors emissions during the historical period (1850–2000). Future emissions of  
21 ozone precursors (e.g. CO and NO<sub>x</sub>) are fairly similar among the RCPs scenarios,  
22 decreasing to various degrees between the present-day and 2100 (van Vuuren et al.,  
23 2011). The exception is that the methane burden under the RCP8.5 scenario roughly  
24 doubles by the end of the 21<sup>st</sup> century (Meinshausen et al., 2011). Mainly due to the  
25 methane burden and the stratospheric ozone influence via STE, ACCMIP CHEM  
26 tropospheric column ozone change by 2100 relative to present-day is –5.5 DU and 5.2  
27 DU, for the RCP2.6 and RCP8.5 scenarios respectively. For both stratospheric  
28 columns ozone, there is a small decrease from the pre-industrial period to present-day  
29 (–3.2–3.3 DU), which remained fairly constant by 2030 for both RCPs scenarios.  
30 Although ODS concentrations decrease during the 21<sup>st</sup> century, two different stories  
31 occur in the second half of the century. In the upper stratosphere, ozone amounts  
32 return to pre-industrial levels under the low emission scenario by 2100. However,  
33 RCP8.5 2100 ozone levels relative to present-day increase 8.3 DU, due to a slow

1 down of the ozone catalytic loss cycles, linked to the stratospheric cooling (e.g. Haigh  
2 and Pyle, 1982; Portmann and Solomon, 2007; Revell et al., 2012; Reader et al.,  
3 2013). In the lower stratosphere, ozone levels change little ( $-0.8$  DU) by 2100 relative  
4 to the present-day for the RCP2.6, though decrease by  $-8.5$  DU under the RCP8.5  
5 scenario, likely due to the acceleration of the BDC. In summary, stratospheric column  
6 ozone by 2100 remains fairly similar to the present-day, although different stories are  
7 drawn in the upper and lower stratosphere. Future TCO changes in the tropics are  
8 mainly determined by the upper stratospheric ozone sensitivity to GHG  
9 concentrations, due to a large compensation between tropospheric and lower  
10 stratospheric column ozone changes in the RCP2.6 and RCP8.5 emission scenarios.  
11 Notice that tropospheric column ozone in the RCP8.5 2100 time slice is largely the  
12 result of future increase in methane.

13 Figure 5 presents vertically resolved ozone change between the Hist 1850 and RCPs  
14 2100 time slices and between the Hist 2000 and RCPs 2100 time slices (top and  
15 bottom rows, respectively). In contrast to the tropics, the midlatitudes lower  
16 stratospheric ozone is positively correlated to GHG concentrations (Figure 5, b and d)  
17 mainly due to the influx of relatively “rich” ozone air from lower latitudes (e.g.  
18 WMO, 2011) from a strengthened BDC. Additionally, the increase in methane  
19 emissions in the RCP8.5 scenario results in chemically-driven increases in ozone in  
20 this region (e.g. Randeniya et al., 2002; Reader et al., 2013). However, middle and  
21 upper stratospheric ozone sensitivity to GHG concentrations behaves the same as in  
22 the tropics. Substantial ozone increases are simulated by 2100, in the altitude region  
23 of the upper troposphere-lower stratosphere and the middle and upper stratosphere,  
24 relative to pre-industrial (1850) and present-day (2000) levels. We note that climate  
25 impact in ozone levels is weaker in the southern than in the northern midlatitudes for  
26 the ACCMIP and CMIP5 multi-model means, likely due to hemispheric differences in  
27 STE and ozone flux (Shepherd, 2008), which is in contrast to IGAC/SPARC data set.  
28 TCO for the RCP8.5 2100 time slice is 6.9-13.1 % higher than those simulated in the  
29 Hist 1850 time slice. While, the RCP2.6 2100 time slice in the northern midlatitudes  
30 is similar to present-day levels, in the southern midlatitudes is similar to pre-industrial  
31 levels. This is mainly due to regional differences in ozone precursors emissions and  
32 the tropospheric ozone contribution (Figure 3, c-d).

1 Over the Arctic in boreal spring (Figure 3e), results similar to those in the northern  
2 midlatitudes are found for all models, though higher stratospheric ozone sensitivity to  
3 GHG concentrations lead to approximately two times larger scenario differences for  
4 the 2100 time slice (37.7 DU between RCP2.6 and RCP8.5). In addition to the  
5 RCP8.5 emission scenario, ozone super recovery is also simulated under the RCP2.6  
6 scenario by ACCMIP and CMIP5 CHEM models. The IGAC/SPARC data set  
7 projects similar results to those under the latter scenario. Note that the ACCMIP and  
8 CMIP5 multi-model means show a small increase in TCO by 1980 and no significant  
9 ozone depletion by 2000 relative to 1850. This is in sharp contrast to the polar region  
10 in the SH, which highlights both regional differences in ozone precursors sources and  
11 atmospheric conditions.

12 Over Antarctica during austral spring (Figure 3f), TCO evolution is more isolated  
13 from GHG effects and ozone precursors than in other regions. In agreement with  
14 previous studies, ACCMIP and CMIP5 CHEM models project similar values under  
15 the lower and higher GHG scenarios (Austin et al., 2010; SPARC-CCMVal, 2010;  
16 Eyring et al., 2013). TCO in the RCPs 2100 time slices remained below 1850s levels  
17 (-3.3–6.7 %). This suggests decreasing ODS concentrations during the 21<sup>st</sup> century as  
18 the main driver of stratospheric ozone in this region and season (i.e. ozone super-  
19 recovery is found for RCP8.5 2100 in other seasons). Furthermore, vertical  
20 distribution changes of stratospheric ozone in 2100, compared to 1850 (Figure 5f1),  
21 and 2000 (Figure 5f2), show small differences between the above scenarios (e.g.  
22 small sensitivity to GHG concentrations). Evolution of stratospheric ozone at high  
23 latitudes in the SH, particularly during spring season, has implications over surface  
24 climate due to modifications in temperature and circulation patterns.

25

#### 26 **4 Stratospheric ozone changes and associated climate impacts in the** 27 **Southern Hemisphere**

28 To probe stratospheric ozone evolution and climate interactions (1850–2100), we first  
29 examine simulated stratospheric temperatures in Section 4.1. SAM index evolution is  
30 presented in Section 4.2. Note that ozone loss over the Arctic in boreal spring is only  
31 around 25 % of the depletion observed in the Antarctic (see also Figure 1e), and is not

1 believed to have a significant role in driving NH surface climate (e.g. Grise et al.,  
2 2009; Eyring et al., 2010a; Morgenstern et al., 2010a).

### 3 **4.1 Lower stratospheric temperatures changes**

4 Figure 6 shows recent stratospheric temperature decadal trends (1980–2000) in polar  
5 regions during springtime (March-April-May in the Arctic and October-November-  
6 December in the Antarctic). The figure compares temperature in the lower  
7 stratosphere (TLS) in the ACCMIP, CMIP5 and CCMVal2 models with observational  
8 estimates based on Microwave Sounding Unit (MSU) retrievals by the Remote  
9 Sensing Systems (RSS - version 3.3) (Mears et al., 2011), the Satellite Applications  
10 and Research (STAR - version 3.0) (Zou et al., 2006; Zou et al., 2009), and the  
11 University of Alabama in Huntsville (UAH - version 5.4) (Christy et al., 2003)  
12 (Figure 6a-c). The TLS vertical weighting function from RSS is used to derive MSU  
13 temperature from climate models output. Temperature vertical profile decadal trends  
14 in the ACCMIP models (Figure 6b-d) are compared against radiosonde products of  
15 the Radiosonde Observation Correction Using Reanalyses (RAOBCORE - version  
16 1.5), Radiosonde Innovation Composite Homogenization (RICH-obs and RICH-tau -  
17 version 1.5) (Haimberger et al., 2008, 2012), the Hadley Centre radiosonde  
18 temperature product (HadAT2) (Thorne et al., 2005), and the Iterative Universal  
19 Kriging (IUK) Radiosonde Analysis Project (Sherwood et al., 2008) (version 2.01).

20 Over the NH polar cap in boreal spring, although ACCMIP, CMIP5 and CCMVal2  
21 models are within observational estimates, all simulates weaker decadal trends ( $-0.5$ ,  
22  $-0.1$  and  $-0.4$  K dec<sup>-1</sup>, respectively) than observed ( $-1.6 \pm 3.4$  K dec<sup>-1</sup>) (Figure 6a).  
23 This is likely due to the abnormally cold boreal winters in the mid-1990s (i.e. more  
24 PSCs formation), which resulted in enhanced ozone loss during boreal spring  
25 (Newman et al., 2001). Natural variability in models not constrained by observed  
26 meteorology is difficult to reproduce (Austin et al., 2003; Charlton-Perez et al., 2010;  
27 Butchart et al., 2011; Charlton-Perez et al., 2013; Shepherd et al., 2014). Moreover,  
28 ACCMIP simulations, based on time slice experiments for most models, did not  
29 embrace that period, only those boundary conditions for 1980 and 2000 years. This  
30 weaker trend on stratospheric temperature is also seen in the vertical profile above  
31 around the tropopause (Figure 6b).

1 Over Antarctica in austral spring, the ACCMIP and CMIP5 multi-model means are in  
2 very good agreement ( $-2.2 \text{ K dec}^{-1}$ ,  $-2.5 \text{ K dec}^{-1}$  respectively) with satellite  
3 measurements ( $-2.1 \pm 6.3 \text{ K dec}^{-1}$ ) (Figure 6c). CHEM models (i.e. ACCMIP and  
4 CMIP5) and CCMVal2 multi-model mean tend to simulate larger negative trends than  
5 NOCHEM models, which may be due to the fact that the IGAC/SPARC ozone data  
6 set is at the lower end of the observational estimates as has been shown in (Solomon  
7 et al., 2012; Hassler et al., 2013; Young et al., 2014). They argued the importance of  
8 the ozone data set for appropriate representation of stratospheric temperature, and in  
9 turn SH surface climate. Although, large uncertainties exist in this region and period,  
10 all ACCMIP individual models fall within the observational error estimates (Figure  
11 6d). Note that observational estimates are significant at the 95 % confidence levels, if  
12 year 2000 is removed from the linear fit ( $-2.95 \pm 2.90$ ,  $-3.02 \pm 2.95$  and  $-3.12 \pm 2.87$   
13  $\text{K dec}^{-1}$  for the RSS, STAR and UAH data sets, respectively), as this year was  
14 “anomalously” warm. The relatively large spread of the simulated stratospheric  
15 temperature trend for the observational period is consistent with the models spread of  
16 ozone in this region (Figures 1f and 2f). The correlation between stratospheric ozone  
17 and temperature trends becomes evident by comparing TCO trends between the Hist  
18 1980 and 2000 time slices and TLS trends for the same period between CHEM and  
19 NOCHEM models (i.e. large ozone depletion results in stronger stratospheric cooling  
20 trends).

21 Figure 7a depicts SH polar cap TLS long-term evolution (1850–2100) normalised to  
22 pre-industrial levels during austral spring. As commented above, stratospheric  
23 temperature can be perturbed by anthropogenic emissions of ODS and GHG, both  
24 having a net cooling effect. ACCMIP Hist 1980 and 2000 TLS time slices ( $-3.4 \text{ K}$   
25 and  $-7.9 \text{ K}$ ) are driven by the combination of ozone depletion and climate change  
26 since the pre-industrial period. In future projections, ozone recovery and GHG  
27 concentrations are expected to have an opposite effect on stratospheric temperatures.  
28 The slight temperature increased of the TLS by 2030 in the RCPs time slices relative  
29 to present-day, is very similar between the lower and higher RCPs emission scenarios  
30 ( $1.6 \text{ K}$  and  $1.2 \text{ K}$ , respectively). By the end of the 21<sup>st</sup> century, the projected TLS  
31 under the RCP2.6 scenario returns to Hist 1980 levels, whereas it remains fairly  
32 unchanged under the RCP8.5 scenario relative to 2030. These two different stories  
33 suggest a key role of GHG concentration in the second half of the century, with

1 significant implications for many aspects of the SH surface climate as reported  
2 previously (McLandress et al., 2011; Perlwitz, 2011; Polvani et al., 2011); see Section  
3 4.2 and Thompson et al. (2011) and Previdi and Polvani (2014) for a comprehensive  
4 review.

## 5 **4.2 Southern Annular Mode evolution**

6 The SAM index is defined as per Gong and Wang (1999), by subtracting the zonal  
7 mean sea level pressure (SLP) at 65°S latitude from the zonal mean SLP at 40°S  
8 latitude from monthly mean output. The SAM index is a proxy of variability in the  
9 jets captured by SLP anomalies at middle and high latitudes (e.g. Thompson and  
10 Wallace, 2000).

11 Figure 7b shows SAM index long-term evolution (1850–2100) normalised to 1850  
12 levels during austral summer. Observational estimates based on the Hadley Centre  
13 Sea Level Pressure data set (HadSLP2) are shown from 1970 to 2012. The ACCMIP  
14 multi-model mean shows a positive trend between Hist 1980 and 2000 time slices (1.3  
15 hPa dec<sup>-1</sup>), coinciding with the highest ozone depletion period. Within uncertainty,  
16 this is weaker than observational estimates ( $2.2 \pm 1.1$  hPa dec<sup>-1</sup>). ACCMIP CHEM  
17 and NOCHEM models show similar SAM index trends, although the latter presents  
18 weaker TLS trends (see Figure 6c). As seen in Figure 7a for the TLS in austral spring,  
19 by 2030 for both RCPs scenarios the ACCMIP multi-model mean shows a slight  
20 decrease in the SAM index relative to Hist 2000.

21 Two different stories are drawn from 2030 to 2100. The SAM index simulated under  
22 the RCP2.6 scenario tends to return to ‘normal’ levels ( $-0.4$  hPa dec<sup>-1</sup>), as ODS  
23 concentrations and GHG emissions decrease during the second half of the century. In  
24 contrast, under the RCP8.5 scenario GHG concentrations increase, resulting in a  
25 positive trend of the SAM index ( $0.3$  hPa dec<sup>-1</sup>). By using two independent samples  
26 Student’s t test, we find that SAM index changes between Hist 2000 and 2100 relative  
27 to Hist 1850, are significant for the RCP2.6 at the 5 % level, although is not  
28 significant for the RCP8.5. CMIP5 multi-model mean shows better agreement with  
29 observations during the record period ( $2.1$  hPa dec<sup>-1</sup>) than ACCMIP. During the  
30 second half of the 21<sup>st</sup> century (2030–2100), however, the CMIP5 multi-model mean  
31 shows consistent projections with the latter ( $-0.4$  hPa dec<sup>-1</sup> and  $0.4$  hPa dec<sup>-1</sup> for  
32 RCP2.6 and RCP8.5, respectively).

1

## 2 **5 Discussion**

3 TCO trends in ACCMIP models compare favourably with observations, however,  
4 smaller ozone negative trends in the tropical lower stratosphere are simulated. It has  
5 been argued that tropical upwelling (or the BDC) is the main driver in this region  
6 determining ozone levels (Lamarque and Solomon, 2010; Polvani and Solomon,  
7 2012), with chemical processes playing a minor role (e.g. Meul et al., 2014).  
8 However, observed BDC and its seasonal cycle (Fu et al., 2010; Young et al., 2011)  
9 are poorly constrained in modelling studies (e.g. Butchart et al., 2006; Garcia and  
10 Randel, 2008; Butchart et al., 2010). This is important since ozone depletion  
11 determines to a large extent the temperatures in the lower stratosphere (e.g. Polvani  
12 and Solomon, 2012) (note that ACCMIP models show smaller negative temperature  
13 trends in this region compared to observations, not shown), and the latter triggers  
14 significant feedbacks in climate response (Stevenson, 2015). Models with less ozone  
15 depletion in the tropical lower stratosphere may have stronger climate sensitivity  
16 (Dietmüller et al., 2014; Nowack et al., 2015).

17 Long-term TCO changes relative to Hist 1850 in the ACCMIP models considered in  
18 this study, are least consistent for Hist 2000 in the Antarctic springtime (i.e. the period  
19 with large ozone losses) and for RCP8.5 2100 in general. The latter may be linked to  
20 uncertainties due to sensitivity of ozone to future GHG emissions (i.e. various direct  
21 and indirect processes affecting ozone amounts in the troposphere and the  
22 stratosphere). For example, CO<sub>2</sub> and methane mixing ratios increase by more than 3  
23 and 4 times in RCP8.5 2100 relative to the pre-industrial period, respectively.  
24 Nevertheless, the ACCMIP and CMIP5 multi-model means, show consistent RCP8.5  
25 2100 projections. Although TCO changes are relative to the Hist 1850, a period  
26 without direct measurements (e.g. estimates with large uncertainties), ACCMIP  
27 models show good agreement compared to other time slices. For example, the  
28 interquartile range (central 50 % of the data) varies approximately 3–8 % of the  
29 corresponding mean value across the regions and seasons considered here.

30 Stratospheric ozone has been shown to be asymmetrical over the SH polar cap  
31 (Grytsai et al., 2007). Prescribing zonal mean ozone fields in CCMs may have  
32 implications on SH climate (e.g. Crook et al., 2008; Gillett et al., 2009), particularly

1 in early spring stratospheric temperatures (September-October) and, though less  
2 pronounced in November-December (Calvo et al., 2012; Young et al., 2013b). During  
3 strong depletion periods such as, in the recent past (1980–2000) and in the near-future  
4 (2000–2030), eliminating zonal asymmetry may result in a poor representation of  
5 stratospheric and tropospheric climate trends in the SH (Waugh et al., 2009b).  
6 Moreover, prescribing stratospheric ozone may lead to inconsistencies and skew the  
7 climate response (e.g. Nowack et al., 2015). We showed that NOCHEM models  
8 simulated both weaker springtime TLS negative trends over the Antarctic compared  
9 to observational estimates, and stronger positive trends in the near-future compared to  
10 CHEM models. In addition, Young et al. (2014) found 20-100 % larger tropospheric  
11 climate responses in this region and season with a climate model driven by the BDBP  
12 data set compared to the SPARC/IGAC data set used in NOCHEM models here.  
13 ACCMIP CHEM and NOCHEM models show most disagreement on SAM index  
14 trends in the near-future, period with relatively strong ozone depletion (>Hist 1980).  
15 The former projects negligible trends compared to  $-0.57 \text{ hPa dec}^{-1}$  and three times  
16 weaker negative trends than the latter, for the RCP2.6 and RCP8.5 respectively. This  
17 is consistent with CHEM and NOCHEM TLS springtime trends in this period and  
18 region. Nevertheless, ACCMIP models participating in this study agree with previous  
19 observational (e.g. Thompson and Solomon, 2002; Marshall, 2003, 2007) and  
20 modelling studies (e.g. Gillett and Thompson, 2003; Son et al., 2008; Son et al., 2009;  
21 Polvani et al., 2010; Son et al., 2010; Arblaster et al., 2011; McLandress et al., 2011;  
22 Polvani et al., 2011; Gillett and Fyfe, 2013; Keeble et al., 2014) on the SH surface  
23 climate response, measured here using the SAM index.

24

## 25 **6 Summary and conclusions**

26 This study has analysed stratospheric ozone evolution from 1850 to 2100 from a  
27 group of chemistry climate models with either prescribed or interactively resolved  
28 time-varying ozone in the stratosphere and participated in the ACCMIP activity (8 out  
29 of 16 models). We have evaluated TCO and vertically resolved ozone trends between  
30 1980 and 2000, and examined past and future ozone projections under the low and  
31 high RCPs future emission scenarios (RCP2.6 and RCP8.5, respectively). Finally, we  
32 have assessed TLS and temperature profile trends at high latitudes in the recent past,

1 and analysed TLS and SH surface climate response (diagnosed using the SAM index),  
2 from the pre-industrial period to the end of the 21<sup>st</sup> century.

3 Within uncertainty estimates, the ACCMIP multi-model mean TCO compares  
4 favourably with recent observational trends (1980–2000), although individual models  
5 often show significant deviations, particularly those models that include interactive  
6 chemistry. The closest agreement of TCO to observations is found over the Antarctic  
7 in austral spring (the ozone hole). The largest disagreement with observations is found  
8 for NH high latitudes during boreal spring, although this is may be due to a series of  
9 cold winters and associated additional PSCs formation during the mid- 1990s  
10 (Newman et al., 2001) – driving stronger ozone depletion – which are not captured by  
11 the use of time slice integrations (Hist 1980 and 2000). In addition, over the tropics  
12 the ACCMIP models fail to simulate ozone reductions in the lower stratosphere over  
13 the same period, which could be linked to trends in tropical upwelling (e.g. Polvani  
14 and Solomon, 2012).

15 The results corroborate previous findings (Waugh et al., 2009a; Eyring et al., 2010b;  
16 Eyring et al., 2013), suggesting that changes in stratospheric ozone due to future  
17 increases in GHG concentrations are most sensitive over the Arctic and the NH  
18 midlatitudes (37.7 DU and 16.1 DU difference between the RCP2.6 and RCP8.5 by  
19 2100, respectively), with the smallest sensitivity in the tropics and over Antarctica  
20 (2.5 DU and 8.1 DU respectively). In the tropics, upper stratospheric ozone sensitivity  
21 to GHG concentrations will largely determine TCO future evolution, due to a trade-  
22 off between lower stratospheric and tropospheric columns ozone during the 21<sup>st</sup>  
23 century under the RCP2.6 and RCP8.5 emission scenarios.

24 The ACCMIP simulations of the trends in TLS and temperature profile over  
25 1980–2000 agree well with satellite and radiosonde observations over the Antarctic in  
26 austral spring. ACCMIP CHEM models agree better with observations than the  
27 CMIP5 CHEM ensemble used here for the same period and region. However,  
28 ACCMIP models using prescribed time-varying stratospheric ozone (NOCHEM)  
29 show weaker trends than observational estimates in the recent past (1980–2000), and  
30 stronger positive trends than models with stratospheric chemistry online (CHEM) in  
31 the near-future (2000–2030). This highlights the importance of the ozone database  
32 used to drive models on the climate response. For example, Young et al. (2014) found

1 large differences in SH surface climate responses when using different ozone data  
2 sets.

3 Overall, stratospheric ozone and associated climate impacts are fairly well represented  
4 by the ACCMIP ensemble mean in the recent past (1980–2000), and individual  
5 models also agree on the sign and distribution of past and future changes  
6 (1850–2100). In line with previous multi-model analyses (Son et al., 2008; Eyring et  
7 al., 2010a; Son et al., 2010; Eyring et al., 2013; Gillett and Fyfe, 2013), and  
8 observation studies (Thompson and Solomon, 2002; Marshall, 2003, 2007), the  
9 ACCMIP models show strong positive trends of the SAM index in austral summer  
10 during the ozone depletion period ( $1.3 \text{ hPa dec}^{-1}$  1980–2000), which is in agreement  
11 with observations ( $2.2 \pm 1.1 \text{ hPa dec}^{-1}$ ). While in the recent past both ozone depletion  
12 and increasing GHGs have favoured a strengthening of the SAM during summer,  
13 under projected ozone recovery they will drive the SAM into opposite directions.  
14 Under the low emission scenario, the SAM index tends to return to pre-industrial  
15 levels from around the second half of the 21<sup>st</sup> century ( $-0.4 \text{ hPa dec}^{-1}$  between  
16 2030–2100); i.e. the impact of ozone recovery is stronger than GHG. In contrast, with  
17 the higher emission scenario, the GHG-driven SAM trend exceeds the opposing ozone  
18 recovery-driven trend, and the SAM index continues on its positive trend ( $0.3 \text{ hPa}$   
19  $\text{dec}^{-1}$  between 2030–2100).

20 In this study we have presented stratospheric ozone evolution (1850–2100) using a  
21 number of models that participated in the ACCMIP activity. We have demonstrated  
22 both its key role in the present and future SH climate and the importance of how it is  
23 represented in climate models. These results and work over the last decade have  
24 shown that changes in stratospheric ozone are tightly coupled to the climate (e.g.  
25 SPARC-CCMVal, 2010; Nowack et al., 2015), supporting the idea of including these  
26 processes interactively in models. It is clear that our ability to understand future  
27 climate will depend on models that can reliably simulate these chemistry-climate  
28 feedbacks.

29

## 1 **References**

- 2 Arblaster, J. M., and Meehl, G. A.: Contributions of External Forcings to Southern  
3 Annular Mode Trends, *J. Clim.*, 19, 2896-2905, 10.1175/JCLI3774.1, 2006.
- 4 Arblaster, J. M., Meehl, G. A., and Karoly, D. J.: Future climate change in the  
5 Southern Hemisphere: Competing effects of ozone and greenhouse gases, *Geophys.*  
6 *Res. Lett.*, 38, L02701, 10.1029/2010GL045384, 2011.
- 7 Austin, J., Shindell, D., Beagley, S. R., Brühl, C., Dameris, M., Manzini, E.,  
8 Nagashima, T., Newman, P., Pawson, S., Pitari, G., Rozanov, E., Schnadt, C., and  
9 Shepherd, T. G.: Uncertainties and assessments of chemistry-climate models of the  
10 stratosphere, *Atmos. Chem. Phys.*, 3, 1-27, 10.5194/acp-3-1-2003, 2003.
- 11 Austin, J., and Wilson, R. J.: Ensemble simulations of the decline and recovery of  
12 stratospheric ozone, *J. Geophys. Res.*, 111, D16314, 10.1029/2005JD006907, 2006.
- 13 Austin, J., Scinocca, J., Plummer, D., Oman, L., Waugh, D., Akiyoshi, H., Bekki, S.,  
14 Braesicke, P., Butchart, N., Chipperfield, M., Cugnet, D., Dameris, M., Dhomse, S.,  
15 Eyring, V., Frith, S., Garcia, R. R., Garny, H., Gettelman, A., Hardiman, S. C.,  
16 Kinnison, D., Lamarque, J. F., Mancini, E., Marchand, M., Michou, M., Morgenstern,  
17 O., Nakamura, T., Pawson, S., Pitari, G., Pyle, J., Rozanov, E., Shepherd, T. G.,  
18 Shibata, K., Teyssède, H., Wilson, R. J., and Yamashita, Y.: Decline and recovery of  
19 total column ozone using a multimodel time series analysis, *J. Geophys. Res.*, 115,  
20 D00M10, 10.1029/2010JD013857, 2010.
- 21 Barnes, E. A., Barnes, N. W., and Polvani, L. M.: Delayed Southern Hemisphere  
22 Climate Change Induced by Stratospheric Ozone Recovery, as Projected by the  
23 CMIP5 Models, *J. Clim.*, 27, 852-867, 10.1175/JCLI-D-13-00246.1, 2013.
- 24 Bodeker, G. E., Shiona, H., and Eskes, H.: Indicators of Antarctic ozone depletion,  
25 *Atmos. Chem. Phys.*, 5, 2603-2615, 10.5194/acp-5-2603-2005, 2005.
- 26 Bodeker, G. E., Hassler, B., Young, P. J., and Portmann, R. W.: A vertically resolved,  
27 global, gap-free ozone database for assessing or constraining global climate model  
28 simulations, *Earth Syst. Sci. Data*, 5, 31-43, 10.5194/essd-5-31-2013, 2013.
- 29 Bönisch, H., Engel, A., Birner, T., Hoor, P., Tarasick, D. W., and Ray, E. A.: On the  
30 structural changes in the Brewer-Dobson circulation after 2000, *Atmos. Chem. Phys.*,  
31 11, 3937-3948, 10.5194/acp-11-3937-2011, 2011.
- 32 Bowman, K. W., Shindell, D. T., Worden, H. M., Lamarque, J. F., Young, P. J.,  
33 Stevenson, D. S., Qu, Z., de la Torre, M., Bergmann, D., Cameron-Smith, P. J.,  
34 Collins, W. J., Doherty, R., Dalsøren, S. B., Faluvegi, G., Folberth, G., Horowitz, L.  
35 W., Josse, B. M., Lee, Y. H., MacKenzie, I. A., Myhre, G., Nagashima, T., Naik, V.,  
36 Plummer, D. A., Rumbold, S. T., Skeie, R. B., Strode, S. A., Sudo, K., Szopa, S.,  
37 Voulgarakis, A., Zeng, G., Kulawik, S. S., Aghedo, A. M., and Worden, J. R.:  
38 Evaluation of ACCMIP outgoing longwave radiation from tropospheric ozone using  
39 TES satellite observations, *Atmos. Chem. Phys.*, 13, 4057-4072, 10.5194/acp-13-  
40 4057-2013, 2013.
- 41 Butchart, N., Scaife, A. A., Bourqui, M., de Grandpré, J., Hare, S. H. E.,  
42 Kettleborough, J., Langematz, U., Manzini, E., Sassi, F., Shibata, K., Shindell, D., and  
43 Sigmund, M.: Simulations of anthropogenic change in the strength of the Brewer-  
44 Dobson circulation, *Clim. Dynam.*, 27, 727-741, 10.1007/s00382-006-0162-4, 2006.

1 Butchart, N., Cionni, I., Eyring, V., Shepherd, T. G., Waugh, D. W., Akiyoshi, H.,  
2 Austin, J., Brühl, C., Chipperfield, M. P., Cordero, E., Dameris, M., Deckert, R.,  
3 Dhomse, S., Frith, S. M., Garcia, R. R., Gettelman, A., Giorgetta, M. A., Kinnison, D.  
4 E., Li, F., Mancini, E., McLandress, C., Pawson, S., Pitari, G., Plummer, D. A.,  
5 Rozanov, E., Sassi, F., Scinocca, J. F., Shibata, K., Steil, B., and Tian, W.:  
6 Chemistry–Climate Model Simulations of Twenty-First Century Stratospheric  
7 Climate and Circulation Changes, *J. Clim.*, 23, 5349-5374, 10.1175/2010JCLI3404.1,  
8 2010.

9 Butchart, N., Charlton-Perez, A. J., Cionni, I., Hardiman, S. C., Haynes, P. H.,  
10 Krüger, K., Kushner, P. J., Newman, P. A., Osprey, S. M., Perlwitz, J., Sigmond, M.,  
11 Wang, L., Akiyoshi, H., Austin, J., Bekki, S., Baumgaertner, A., Braesicke, P., Brühl,  
12 C., Chipperfield, M., Dameris, M., Dhomse, S., Eyring, V., Garcia, R., Garny, H.,  
13 Jöckel, P., Lamarque, J. F., Marchand, M., Michou, M., Morgenstern, O., Nakamura,  
14 T., Pawson, S., Plummer, D., Pyle, J., Rozanov, E., Scinocca, J., Shepherd, T. G.,  
15 Shibata, K., Smale, D., Teyssèdre, H., Tian, W., Waugh, D., and Yamashita, Y.:  
16 Multimodel climate and variability of the stratosphere, *J. Geophys. Res.*, 116,  
17 D05102, 10.1029/2010JD014995, 2011.

18 Butchart, N.: The Brewer-Dobson circulation, *Rev. Geophys.*, 52, 157-184,  
19 10.1002/2013RG000448, 2014.

20 Calvo, N., Garcia, R. R., Marsh, D. R., Mills, M. J., Kinnison, D. E., and Young, P. J.:  
21 Reconciling modeled and observed temperature trends over Antarctica, *Geophys. Res.*  
22 *Lett.*, 39, L16803, 10.1029/2012gl052526, 2012.

23 Charlton-Perez, A. J., Hawkins, E., Eyring, V., Cionni, I., Bodeker, G. E., Kinnison,  
24 D. E., Akiyoshi, H., Frith, S. M., Garcia, R., Gettelman, A., Lamarque, J. F.,  
25 Nakamura, T., Pawson, S., Yamashita, Y., Bekki, S., Braesicke, P., Chipperfield, M.  
26 P., Dhomse, S., Marchand, M., Mancini, E., Morgenstern, O., Pitari, G., Plummer, D.,  
27 Pyle, J. A., Rozanov, E., Scinocca, J., Shibata, K., Shepherd, T. G., Tian, W., and  
28 Waugh, D. W.: The potential to narrow uncertainty in projections of stratospheric  
29 ozone over the 21st century, *Atmos. Chem. Phys.*, 10, 9473-9486, 10.5194/acp-10-  
30 9473-2010, 2010.

31 Charlton-Perez, A. J., Baldwin, M. P., Birner, T., Black, R. X., Butler, A. H., Calvo,  
32 N., Davis, N. A., Gerber, E. P., Gillett, N., Hardiman, S., Kim, J., Krüger, K., Lee, Y.-  
33 Y., Manzini, E., McDaniel, B. A., Polvani, L., Reichler, T., Shaw, T. A., Sigmond,  
34 M., Son, S.-W., Toohey, M., Wilcox, L., Yoden, S., Christiansen, B., Lott, F.,  
35 Shindell, D., Yukimoto, S., and Watanabe, S.: On the lack of stratospheric dynamical  
36 variability in low-top versions of the CMIP5 models, *J. Geophys. Res.*, 118, 2494-  
37 2505, 10.1002/jgrd.50125, 2013.

38 Christy, J. R., Spencer, R. W., Norris, W. B., Braswell, W. D., and Parker, D. E.:  
39 Error Estimates of Version 5.0 of MSU–AMSU Bulk Atmospheric Temperatures, *J.*  
40 *Atmos. Ocean. Tech.*, 20, 613-629, 10.1175/1520-  
41 0426(2003)20<613:EEOVOM>2.0.CO;2, 2003.

42 Cionni, I., Eyring, V., Lamarque, J. F., Randel, W. J., Stevenson, D. S., Wu, F.,  
43 Bodeker, G. E., Shepherd, T. G., Shindell, D. T., and Waugh, D. W.: Ozone database  
44 in support of CMIP5 simulations: results and corresponding radiative forcing, *Atmos.*  
45 *Chem. Phys.*, 11, 11267-11292, 10.5194/acp-11-11267-2011, 2011.

1 Collins, W. J., Derwent, R. G., Garnier, B., Johnson, C. E., Sanderson, M. G., and  
2 Stevenson, D. S.: Effect of stratosphere-troposphere exchange on the future  
3 tropospheric ozone trend, *J. Geophys. Res.*, 108, 8528, 10.1029/2002JD002617, 2003.

4 Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P.,  
5 Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor,  
6 F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S.:  
7 Development and evaluation of an Earth-System model – HadGEM2, *Geosci. Model*  
8 *Dev.*, 4, 1051-1075, 10.5194/gmd-4-1051-2011, 2011.

9 Crook, J. A., Gillett, N. P., and Keeley, S. P. E.: Sensitivity of Southern Hemisphere  
10 climate to zonal asymmetry in ozone, *Geophys. Res. Lett.*, 35, L07806,  
11 10.1029/2007GL032698, 2008.

12 Dietmüller, S., Ponater, M., and Sausen, R.: Interactive ozone induces a negative  
13 feedback in CO<sub>2</sub>-driven climate change simulations, *J. Geophys. Res.*, 119, 1796-  
14 1805, 10.1002/2013JD020575, 2014.

15 Donner, L. J., Wyman, B. L., Hemler, R. S., Horowitz, L. W., Ming, Y., Zhao, M.,  
16 Golaz, J.-C., Ginoux, P., Lin, S. J., Schwarzkopf, M. D., Austin, J., Alaka, G., Cooke,  
17 W. F., Delworth, T. L., Freidenreich, S. M., Gordon, C. T., Griffies, S. M., Held, I.  
18 M., Hurlin, W. J., Klein, S. A., Knutson, T. R., Langenhorst, A. R., Lee, H.-C., Lin,  
19 Y., Magi, B. I., Malyshev, S. L., Milly, P. C. D., Naik, V., Nath, M. J., Pincus, R.,  
20 Ploshay, J. J., Ramaswamy, V., Seman, C. J., Shevliakova, E., Sirutis, J. J., Stern, W.  
21 F., Stouffer, R. J., Wilson, R. J., Winton, M., Wittenberg, A. T., and Zeng, F.: The  
22 Dynamical Core, Physical Parameterizations, and Basic Simulation Characteristics of  
23 the Atmospheric Component AM3 of the GFDL Global Coupled Model CM3, *J.*  
24 *Clim.*, 24, 3484-3519, 10.1175/2011JCLI3955.1, 2011.

25 Dvortsov, V. L., and Solomon, S.: Response of the stratospheric temperatures and  
26 ozone to past and future increases in stratospheric humidity, *J. Geophys. Res.*, 106,  
27 7505-7514, 10.1029/2000JD900637, 2001.

28 Engel, A., Mobius, T., Bonisch, H., Schmidt, U., Heinz, R., Levin, I., Atlas, E., Aoki,  
29 S., Nakazawa, T., Sugawara, S., Moore, F., Hurst, D., Elkins, J., Schauffler, S.,  
30 Andrews, A., and Boering, K.: Age of stratospheric air unchanged within  
31 uncertainties over the past 30 years, *Nature Geosci.*, 2, 28-31, doi: 10.1038/ngeo388,  
32 2009.

33 Eyring, V., Butchart, N., Waugh, D. W., Akiyoshi, H., Austin, J., Bekki, S., Bodeker,  
34 G. E., Boville, B. A., Brühl, C., Chipperfield, M. P., Cordero, E., Dameris, M.,  
35 Deushi, M., Fioletov, V. E., Frith, S. M., Garcia, R. R., Gettelman, A., Giorgetta, M.  
36 A., Grewe, V., Jourdain, L., Kinnison, D. E., Mancini, E., Manzini, E., Marchand, M.,  
37 Marsh, D. R., Nagashima, T., Newman, P. A., Nielsen, J. E., Pawson, S., Pitari, G.,  
38 Plummer, D. A., Rozanov, E., Schraner, M., Shepherd, T. G., Shibata, K., Stolarski,  
39 R. S., Struthers, H., Tian, W., and Yoshiki, M.: Assessment of temperature, trace  
40 species, and ozone in chemistry-climate model simulations of the recent past, *J.*  
41 *Geophys. Res.*, 111, D22308, 10.1029/2006JD007327, 2006.

42 Eyring, V., Waugh, D. W., Bodeker, G. E., Cordero, E., Akiyoshi, H., Austin, J.,  
43 Beagley, S. R., Boville, B. A., Braesicke, P., Brühl, C., Butchart, N., Chipperfield, M.  
44 P., Dameris, M., Deckert, R., Deushi, M., Frith, S. M., Garcia, R. R., Gettelman, A.,  
45 Giorgetta, M. A., Kinnison, D. E., Mancini, E., Manzini, E., Marsh, D. R., Matthes,  
46 S., Nagashima, T., Newman, P. A., Nielsen, J. E., Pawson, S., Pitari, G., Plummer, D.  
47 A., Rozanov, E., Schraner, M., Scinocca, J. F., Semeniuk, K., Shepherd, T. G.,

1 Shibata, K., Steil, B., Stolarski, R. S., Tian, W., and Yoshiki, M.: Multimodel  
2 projections of stratospheric ozone in the 21st century, *J. Geophys. Res.*, 112, D16303,  
3 10.1029/2006JD008332, 2007.

4 Eyring, V., Cionni, I., Bodeker, G. E., Charlton-Perez, A. J., Kinnison, D. E.,  
5 Scinocca, J. F., Waugh, D. W., Akiyoshi, H., Bekki, S., Chipperfield, M. P., Dameris,  
6 M., Dhomse, S., Frith, S. M., Garny, H., Gettelman, A., Kubin, A., Langematz, U.,  
7 Mancini, E., Marchand, M., Nakamura, T., Oman, L. D., Pawson, S., Pitari, G.,  
8 Plummer, D. A., Rozanov, E., Shepherd, T. G., Shibata, K., Tian, W., Braesicke, P.,  
9 Hardiman, S. C., Lamarque, J. F., Morgenstern, O., Pyle, J. A., Smale, D., and  
10 Yamashita, Y.: Multi-model assessment of stratospheric ozone return dates and ozone  
11 recovery in CCMVal-2 models, *Atmos. Chem. Phys.*, 10, 9451-9472, 10.5194/acp-10-  
12 9451-2010, 2010a.

13 Eyring, V., Cionni, I., Lamarque, J. F., Akiyoshi, H., Bodeker, G. E., Charlton-Perez,  
14 A. J., Frith, S. M., Gettelman, A., Kinnison, D. E., Nakamura, T., Oman, L. D.,  
15 Pawson, S., and Yamashita, Y.: Sensitivity of 21st century stratospheric ozone to  
16 greenhouse gas scenarios, *Geophys. Res. Lett.*, 37, L16807, 10.1029/2010GL044443,  
17 2010b.

18 Eyring, V., Arblaster, J. M., Cionni, I., Sedláček, J., Perlwitz, J., Young, P. J., Bekki,  
19 S., Bergmann, D., Cameron-Smith, P., Collins, W. J., Faluvegi, G., Gottschaldt, K.  
20 D., Horowitz, L. W., Kinnison, D. E., Lamarque, J. F., Marsh, D. R., Saint-Martin, D.,  
21 Shindell, D. T., Sudo, K., Szopa, S., and Watanabe, S.: Long-term ozone changes and  
22 associated climate impacts in CMIP5 simulations, *J. Geophys. Res.*, 118, 5029-5060,  
23 10.1002/jgrd.50316, 2013.

24 P.M. Forster, D.W.J. Thompson (Coordinating Lead Authors), M.P. Baldwin, M.P.  
25 Chipperfield, M. Dameris, J.D. Haigh, D.J. Karoly, P.J. Kushner, W.J. Randel, K.H.  
26 Rosenlof, D.J. Seidel, S. Solomon, G. Beig, P. Braesicke, N. Butchart, N.P. Gillett,  
27 K.M. Grise, D.R. Marsh, C. McLandress, T.N. Rao, S.-W. Son, G.L. Stenchikov, and  
28 S. Yoden: Stratospheric changes and climate, Chapter 4 in *Scientific Assessment of*  
29 *Ozone Depletion: 2010*, Global Ozone Research and Monitoring Project–Report  
30 No.52, 516pp., Geneva, Switzerland, World Meteorological Organization, 2011.

31 Fu, Q., Solomon, S., and Lin, P.: On the seasonal dependence of tropical lower-  
32 stratospheric temperature trends, *Atmos. Chem. Phys.*, 10, 2643-2653, 10.5194/acp-  
33 10-2643-2010, 2010.

34 Fyfe, J. C., Boer, G. J., and Flato, G. M.: The Arctic and Antarctic oscillations and  
35 their projected changes under global warming, *Geophys. Res. Lett.*, 26, 1601-1604,  
36 10.1029/1999GL900317, 1999.

37 Garcia, R. R., and Randel, W. J.: Acceleration of the Brewer–Dobson Circulation due  
38 to Increases in Greenhouse Gases, *J. Atmos. Sci.*, 65, 2731-2739,  
39 10.1175/2008JAS2712.1, 2008.

40 Gent, P., Yeager, S., Neale, R., Levis, S., and Bailey, D.: Improvements in a half  
41 degree atmosphere/land version of the CCSM, *Clim. Dynam.*, 34, 819-833,  
42 10.1007/s00382-009-0614-8, 2010.

43 Gillett, N. P., and Thompson, D. W. J.: Simulation of Recent Southern Hemisphere  
44 Climate Change, *Science*, 302, 273-275, 10.1126/science.1087440, 2003.

1 Gillett, N. P., Scinocca, J. F., Plummer, D. A., and Reader, M. C.: Sensitivity of  
2 climate to dynamically-consistent zonal asymmetries in ozone, *Geophys. Res. Lett.*,  
3 36, L10809, 10.1029/2009GL037246, 2009.

4 Gillett, N. P., Akiyoshi, H., Bekki, S., Braesicke, P., Eyring, V., Garcia, R.,  
5 Karpechko, A. Y., McLinden, C. A., Morgenstern, O., Plummer, D. A., Pyle, J. A.,  
6 Rozanov, E., Scinocca, J., and Shibata, K.: Attribution of observed changes in  
7 stratospheric ozone and temperature, *Atmos. Chem. Phys.*, 11, 599-609, 10.5194/acp-  
8 11-599-2011, 2011.

9 Gillett, N. P., and Fyfe, J. C.: Annular mode changes in the CMIP5 simulations,  
10 *Geophys. Res. Lett.*, 40, 1189-1193, 10.1002/grl.50249, 2013.

11 Gong, D., and Wang, S.: Definition of Antarctic Oscillation index, *Geophys. Res.*  
12 *Lett.*, 26, 459-462, 10.1029/1999GL900003, 1999.

13 Gregg, J. W., Jones, C. G., and Dawson, T. E.: Urbanization effects on tree growth in  
14 the vicinity of New York City, *Nature*, 424, 183-187, doi:10.1038/nature01728, 2003.

15 Griffies, S. M., Winton, M., Donner, L. J., Horowitz, L. W., Downes, S. M., Farneti,  
16 R., Gnanadesikan, A., Hurlin, W. J., Lee, H.-C., Liang, Z., Palter, J. B., Samuels, B.  
17 L., Wittenberg, A. T., Wyman, B. L., Yin, J., and Zadeh, N.: The GFDL CM3  
18 Coupled Climate Model: Characteristics of the Ocean and Sea Ice Simulations, *J.*  
19 *Clim.*, 24, 3520-3544, 10.1175/2011JCLI3964.1, 2011.

20 Grise, K. M., Thompson, D. W. J., and Forster, P. M.: On the Role of Radiative  
21 Processes in Stratosphere–Troposphere Coupling, *J. Clim.*, 22, 4154-4161,  
22 10.1175/2009JCLI2756.1, 2009.

23 Grytsai, A. V., Evtushevsky, O. M., Agapitov, O. V., Klekociuk, A. R., and  
24 Milinevsky, G. P.: Structure and long-term change in the zonal asymmetry in  
25 Antarctic total ozone during spring, *Ann. Geophys.*, 25, 361-374, 10.5194/angeo-25-  
26 361-2007, 2007.

27 Haigh, J. D., and Pyle, J. A.: Ozone perturbation experiments in a two-dimensional  
28 circulation model, *Quart. J. Roy. Meteor. Soc.*, 108, 551-574,  
29 10.1002/qj.49710845705, 1982.

30 Haimberger, L., Tavolato, C., and Sperka, S.: Toward Elimination of the Warm Bias  
31 in Historic Radiosonde Temperature Records—Some New Results from a  
32 Comprehensive Intercomparison of Upper-Air Data, *J. Clim.*, 21, 4587-4606,  
33 10.1175/2008JCLI1929.1, 2008.

34 Haimberger, L., Tavolato, C., and Sperka, S.: Homogenization of the Global  
35 Radiosonde Temperature Dataset through Combined Comparison with Reanalysis  
36 Background Series and Neighboring Stations, *J. Clim.*, 25, 8108-8131, 10.1175/JCLI-  
37 D-11-00668.1, 2012.

38 Hassler, B., Young, P. J., Portmann, R. W., Bodeker, G. E., Daniel, J. S., Rosenlof, K.  
39 H., and Solomon, S.: Comparison of three vertically resolved ozone data sets:  
40 climatology, trends and radiative forcings, *Atmos. Chem. Phys.*, 13, 5533-5550,  
41 10.5194/acp-13-5533-2013, 2013.

42 Holton, J. R., Haynes, P. H., McIntyre, M. E., Douglass, A. R., Rood, R. B., and  
43 Pfister, L.: Stratosphere-troposphere exchange, *Rev. Geophys.*, 33, 403-439,  
44 10.1029/95RG02097, 1995.

1 Hsu, J., and Prather, M. J.: Stratospheric variability and tropospheric ozone, *J.*  
2 *Geophys. Res.*, 114, D06102, 10.1029/2008JD010942, 2009.

3 IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working  
4 Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate  
5 Change, Cambridge University Press, Cambridge, United Kingdom and New York,  
6 NY, USA, 1535 pp., 2013.

7 Isaksen, I. S. A., Granier, C., Myhre, G., Berntsen, T. K., Dalsøren, S. B., Gauss, M.,  
8 Klimont, Z., Benestad, R., Bousquet, P., Collins, W., Cox, T., Eyring, V., Fowler, D.,  
9 Fuzzi, S., Jöckel, P., Laj, P., Lohmann, U., Maione, M., Monks, P., Prevo, A. S. H.,  
10 Raes, F., Richter, A., Rognerud, B., Schulz, M., Shindell, D., Stevenson, D. S.,  
11 Storelvmo, T., Wang, W. C., van Weele, M., Wild, M., and Wuebbles, D.:  
12 Atmospheric composition change: Climate–Chemistry interactions, *Atmos. Environ.*,  
13 43, 5138-5192, doi:10.1016/j.atmosenv.2009.08.003, 2009.

14 Jacob, D. J., and Winner, D. A.: Effect of climate change on air quality, *Atmos.*  
15 *Environ.*, 43, 51-63, doi:10.1016/j.atmosenv.2008.09.051, 2009.

16 Jerrett, M., Burnett, R. T., Pope, C. A., Ito, K., Thurston, G., Krewski, D., Shi, Y.,  
17 Calle, E., and Thun, M.: Long-Term Ozone Exposure and Mortality, *New Engl. J.*  
18 *Med.*, 360, 1085-1095, 10.1056/NEJMoa0803894, 2009.

19 Keeble, J., Braesicke, P., Abraham, N. L., Roscoe, H. K., and Pyle, J. A.: The impact  
20 of polar stratospheric ozone loss on Southern Hemisphere stratospheric circulation  
21 and climate, *Atmos. Chem. Phys.*, 14, 13705-13717, 10.5194/acp-14-13705-2014,  
22 2014.

23 Koch, D., Schmidt, G. A., and Field, C. V.: Sulfur, sea salt, and radionuclide aerosols  
24 in GISS ModelE, *J. Geophys. Res.*, 111, D06206, 10.1029/2004JD005550, 2006.

25 Lamarque, J.-F., and Solomon, S.: Impact of Changes in Climate and Halocarbons on  
26 Recent Lower Stratosphere Ozone and Temperature Trends, *J. Clim.*, 23, 2599-2611,  
27 10.1175/2010JCLI3179.1, 2010.

28 Lamarque, J.-F., Kyle, G. P., Meinshausen, M., Riahi, K., Smith, S., van Vuuren, D.,  
29 Conley, A., and Vitt, F.: Global and regional evolution of short-lived radiatively-  
30 active gases and aerosols in the Representative Concentration Pathways, *Clim.*  
31 *Change*, 109, 191-212, 10.1007/s10584-011-0155-0, 2011.

32 Lamarque, J. F., Emmons, L. K., Hess, P. G., Kinnison, D. E., Tilmes, S., Vitt, F.,  
33 Heald, C. L., Holland, E. A., Lauritzen, P. H., Neu, J., Orlando, J. J., Rasch, P. J., and  
34 Tyndall, G. K.: CAM-chem: description and evaluation of interactive atmospheric  
35 chemistry in the Community Earth System Model, *Geosci. Model Dev.*, 5, 369-411,  
36 10.5194/gmd-5-369-2012, 2012.

37 Lamarque, J. F., Dentener, F., McConnell, J., Ro, C. U., Shaw, M., Vet, R.,  
38 Bergmann, D., Cameron-Smith, P., Dalsoren, S., Doherty, R., Faluvegi, G., Ghan, S.  
39 J., Josse, B., Lee, Y. H., MacKenzie, I. A., Plummer, D., Shindell, D. T., Skeie, R. B.,  
40 Stevenson, D. S., Strode, S., Zeng, G., Curran, M., Dahl-Jensen, D., Das, S.,  
41 Fritzsche, D., and Nolan, M.: Multi-model mean nitrogen and sulfur deposition from  
42 the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP):  
43 evaluation of historical and projected future changes, *Atmos. Chem. Phys.*, 13, 7997-  
44 8018, 10.5194/acp-13-7997-2013, 2013a.

1 Lamarque, J. F., Shindell, D. T., Josse, B., Young, P. J., Cionni, I., Eyring, V.,  
2 Bergmann, D., Cameron-Smith, P., Collins, W. J., Doherty, R., Dalsoren, S.,  
3 Faluvegi, G., Folberth, G., Ghan, S. J., Horowitz, L. W., Lee, Y. H., MacKenzie, I.  
4 A., Nagashima, T., Naik, V., Plummer, D., Righi, M., Rumbold, S. T., Schulz, M.,  
5 Skeie, R. B., Stevenson, D. S., Strode, S., Sudo, K., Szopa, S., Voulgarakis, A., and  
6 Zeng, G.: The Atmospheric Chemistry and Climate Model Intercomparison Project  
7 (ACCMIP): overview and description of models, simulations and climate diagnostics,  
8 *Geosci. Model Dev.*, 6, 179-206, 10.5194/gmd-6-179-2013, 2013b.

9 Lary, D. J.: Catalytic destruction of stratospheric ozone, *J. Geophys. Res.*, 102,  
10 21515-21526, 1997.

11 Lee, Y. H., Lamarque, J. F., Flanner, M. G., Jiao, C., Shindell, D. T., Berntsen, T.,  
12 Bisiaux, M. M., Cao, J., Collins, W. J., Curran, M., Edwards, R., Faluvegi, G., Ghan,  
13 S., Horowitz, L. W., McConnell, J. R., Ming, J., Myhre, G., Nagashima, T., Naik, V.,  
14 Rumbold, S. T., Skeie, R. B., Sudo, K., Takemura, T., Thevenon, F., Xu, B., and  
15 Yoon, J. H.: Evaluation of preindustrial to present-day black carbon and its albedo  
16 forcing from Atmospheric Chemistry and Climate Model Intercomparison Project  
17 (ACCMIP), *Atmos. Chem. Phys.*, 13, 2607-2634, 10.5194/acp-13-2607-2013, 2013.

18 Lelieveld, J., and Dentener, F. J.: What controls tropospheric ozone?, *J. Geophys.*  
19 *Res.*, 105, 3531-3551, 10.1029/1999JD901011, 2000.

20 Marshall, G. J.: Trends in the Southern Annular Mode from Observations and  
21 Reanalyses, *J. Clim.*, 16, 4134-4143, 10.1175/1520-  
22 0442(2003)016<4134:TITSAM>2.0.CO;2, 2003.

23 Marshall, G. J., Stott, P. A., Turner, J., Connolley, W. M., King, J. C., and Lachlan-  
24 Cope, T. A.: Causes of exceptional atmospheric circulation changes in the Southern  
25 Hemisphere, *Geophys. Res. Lett.*, 31, L14205, 10.1029/2004GL019952, 2004.

26 Marshall, G. J.: Half-century seasonal relationships between the Southern Annular  
27 mode and Antarctic temperatures, *Int. J. Climatol.*, 27, 373-383, 10.1002/joc.1407,  
28 2007.

29 Martin, G. M., Bellouin, N., Collins, W. J., Culverwell, I. D., Halloran, P. R.,  
30 Hardiman, S. C., Hinton, T. J., Jones, C. D., McDonald, R. E., McLaren, A. J.,  
31 O'Connor, F. M., Roberts, M. J., Rodriguez, J. M., Woodward, S., Best, M. J.,  
32 Brooks, M. E., Brown, A. R., Butchart, N., Dearden, C., Derbyshire, S. H., Dharssi, I.,  
33 Doutriaux-Boucher, M., Edwards, J. M., Falloon, P. D., Gedney, N., Gray, L. J.,  
34 Hewitt, H. T., Hobson, M., Huddleston, M. R., Hughes, J., Ineson, S., Ingram, W. J.,  
35 James, P. M., Johns, T. C., Johnson, C. E., Jones, A., Jones, C. P., Joshi, M. M., Keen,  
36 A. B., Liddicoat, S., Lock, A. P., Maidens, A. V., Manners, J. C., Milton, S. F., Rae, J.  
37 G. L., Ridley, J. K., Sellar, A., Senior, C. A., Totterdell, I. J., Verhoef, A., Vidale, P.  
38 L., and Wiltshire, A.: The HadGEM2 family of Met Office Unified Model climate  
39 configurations, *Geosci. Model Dev.*, 4, 723-757, 10.5194/gmd-4-723-2011, 2011.

40 McLandress, C., Shepherd, T. G., Scinocca, J. F., Plummer, D. A., Sigmund, M.,  
41 Jonsson, A. I., and Reader, M. C.: Separating the Dynamical Effects of Climate  
42 Change and Ozone Depletion. Part II: Southern Hemisphere Troposphere, *J. Clim.*,  
43 24, 1850-1868, 10.1175/2010JCLI3958.1, 2011.

44 McLinden, C. A., Olsen, S. C., Hannegan, B., Wild, O., Prather, M. J., and Sundet, J.:  
45 Stratospheric ozone in 3-D models: A simple chemistry and the cross-tropopause flux,  
46 *J. Geophys. Res.*, 105, 14653-14665, 10.1029/2000JD900124, 2000.

1 McPeters, R. D., Bhartia, P. K., Haffner, D., Labow, G. J., and Flynn, L.: The version  
2 8.6 SBUV ozone data record: An overview, *J. Geophys. Res.*, 118, 8032-8039,  
3 10.1002/jgrd.50597, 2013.

4 Mears, C. A., Wentz, F. J., Thorne, P., and Bernie, D.: Assessing uncertainty in  
5 estimates of atmospheric temperature changes from MSU and AMSU using a Monte-  
6 Carlo estimation technique, *J. Geophys. Res.*, 116, doi:10.1029/2010JD014954, 2011.

7 Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T.,  
8 Lamarque, J. F., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Riahi, K., Thomson,  
9 A., Velders, G. J. M., and Vuuren, D. P. P.: The RCP greenhouse gas concentrations  
10 and their extensions from 1765 to 2300, *Clim. Change*, 109, 213-241,  
11 10.1007/s10584-011-0156-z, 2011.

12 Meul, S., Langematz, U., Oberländer, S., Garny, H., and Jöckel, P.: Chemical  
13 contribution to future tropical ozone change in the lower stratosphere, *Atmos. Chem.*  
14 *Phys.*, 14, 2959-2971, 10.5194/acp-14-2959-2014, 2014.

15 Morgenstern, O., Akiyoshi, H., Bekki, S., Braesicke, P., Butchart, N., Chipperfield,  
16 M. P., Cugnet, D., Deushi, M., Dhomse, S. S., Garcia, R. R., Gettelman, A., Gillett,  
17 N. P., Hardiman, S. C., Jumelet, J., Kinnison, D. E., Lamarque, J. F., Lott, F.,  
18 Marchand, M., Michou, M., Nakamura, T., Olivie, D., Peter, T., Plummer, D., Pyle, J.  
19 A., Rozanov, E., Saint-Martin, D., Scinocca, J. F., Shibata, K., Sigmund, M., Smale,  
20 D., Teysse, H., Tian, W., Voltaire, A., and Yamashita, Y.: Anthropogenic forcing  
21 of the Northern Annular Mode in CCMVal-2 models, *J. Geophys. Res.*, 115,  
22 D00M03, 10.1029/2009JD013347, 2010a.

23 Morgenstern, O., Giorgetta, M. A., Shibata, K., Eyring, V., Waugh, D. W., Shepherd,  
24 T. G., Akiyoshi, H., Austin, J., Baumgaertner, A. J. G., Bekki, S., Braesicke, P.,  
25 Brühl, C., Chipperfield, M. P., Cugnet, D., Dameris, M., Dhomse, S., Frith, S. M.,  
26 Garny, H., Gettelman, A., Hardiman, S. C., Hegglin, M. I., Jöckel, P., Kinnison, D.  
27 E., Lamarque, J. F., Mancini, E., Manzini, E., Marchand, M., Michou, M., Nakamura,  
28 T., Nielsen, J. E., Olivie, D., Pitari, G., Plummer, D. A., Rozanov, E., Scinocca, J. F.,  
29 Smale, D., Teysse, H., Toohey, M., Tian, W., and Yamashita, Y.: Review of the  
30 formulation of present-generation stratospheric chemistry-climate models and  
31 associated external forcings, *J. Geophys. Res.*, 115, D00M02,  
32 10.1029/2009JD013728, 2010b.

33 Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestedt, J., Huang, J., Koch,  
34 D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G.,  
35 Takemura, T., and Zhang, H.: Anthropogenic and Natural Radiative Forcing, in:  
36 *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I*  
37 *to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*,  
38 edited by: Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung,  
39 A. Nauels, Y. Xia, V. Bex and P.M. Midgley, Cambridge University Press,  
40 Cambridge, United Kingdom and New York, NY, USA, 659–740, 2013.

41 Naik, V., Horowitz, L. W., Fiore, A. M., Ginoux, P., Mao, J., Aghedo, A. M., and  
42 Levy, H.: Impact of preindustrial to present-day changes in short-lived pollutant  
43 emissions on atmospheric composition and climate forcing, *J. Geophys. Res.*, 118,  
44 8086-8110, 10.1002/jgrd.50608, 2013a.

45 Naik, V., Voulgarakis, A., Fiore, A. M., Horowitz, L. W., Lamarque, J. F., Lin, M.,  
46 Prather, M. J., Young, P. J., Bergmann, D., Cameron-Smith, P. J., Cionni, I., Collins,

1 W. J., Dalsören, S. B., Doherty, R., Eyring, V., Faluvegi, G., Folberth, G. A., Josse,  
2 B., Lee, Y. H., MacKenzie, I. A., Nagashima, T., van Noije, T. P. C., Plummer, D. A.,  
3 Righi, M., Rumbold, S. T., Skeie, R., Shindell, D. T., Stevenson, D. S., Strode, S.,  
4 Sudo, K., Szopa, S., and Zeng, G.: Preindustrial to present-day changes in  
5 tropospheric hydroxyl radical and methane lifetime from the Atmospheric Chemistry  
6 and Climate Model Intercomparison Project (ACCMIP), *Atmos. Chem. Phys.*, 13,  
7 5277-5298, 10.5194/acp-13-5277-2013, 2013b.

8 Newman, P. A., Nash, E. R., and Rosenfield, J. E.: What controls the temperature of  
9 the Arctic stratosphere during the spring?, *J. Geophys. Res.*, 106, 19999-20010,  
10 10.1029/2000JD000061, 2001.

11 Nowack, P. J., Luke Abraham, N., Maycock, A. C., Braesicke, P., Gregory, J. M.,  
12 Joshi, M. M., Osprey, A., and Pyle, J. A.: A large ozone-circulation feedback and its  
13 implications for global warming assessments, *Nature Clim. Change*, 5, 41-45,  
14 doi:10.1038/nclimate2451, 2015.

15 Parrish, D. D., Lamarque, J. F., Naik, V., Horowitz, L., Shindell, D. T., Staehelin, J.,  
16 Derwent, R., Cooper, O. R., Tanimoto, H., Volz-Thomas, A., Gilge, S., Scheel, H. E.,  
17 Steinbacher, M., and Fröhlich, M.: Long-term changes in lower tropospheric baseline  
18 ozone concentrations: Comparing chemistry-climate models and observations at  
19 northern midlatitudes, *J. Geophys. Res.*, 5719–5736, 10.1002/2013JD021435, 2014.

20 Perlwitz, J., Pawson, S., Fogt, R. L., Nielsen, J. E., and Neff, W. D.: Impact of  
21 stratospheric ozone hole recovery on Antarctic climate, *Geophys. Res. Lett.*, 35,  
22 L08714, 10.1029/2008GL033317, 2008.

23 Perlwitz, J.: Atmospheric science: Tug of war on the jet stream, *Nature Clim. Change*,  
24 1, 29-31, doi:10.1038/nclimate1065, 2011.

25 Polvani, L. M., Waugh, D. W., Correa, G. J. P., and Son, S.-W.: Stratospheric Ozone  
26 Depletion: The Main Driver of Twentieth-Century Atmospheric Circulation Changes  
27 in the Southern Hemisphere, *J. Clim.*, 24, 795-812, 10.1175/2010JCLI3772.1, 2010.

28 Polvani, L. M., Previdi, M., and Deser, C.: Large cancellation, due to ozone recovery,  
29 of future Southern Hemisphere atmospheric circulation trends, *Geophys. Res. Lett.*,  
30 38, L04707, 10.1029/2011GL046712, 2011.

31 Polvani, L. M., and Solomon, S.: The signature of ozone depletion on tropical  
32 temperature trends, as revealed by their seasonal cycle in model integrations with  
33 single forcings, *J. Geophys. Res.*, 117, D17102, 10.1029/2012JD017719, 2012.

34 Portmann, R. W., and Solomon, S.: Indirect radiative forcing of the ozone layer  
35 during the 21st century, *Geophys. Res. Lett.*, 34, L02813, 10.1029/2006GL028252,  
36 2007.

37 Portmann, R. W., Daniel, J. S., and Ravishankara, A. R.: Stratospheric ozone  
38 depletion due to nitrous oxide: influences of other gases, *Philos. T. Roy. Soc. B*, 367,  
39 1256-1264, 10.1098/rstb.2011.0377, 2012.

40 Prather, M. J., Ehhalt, D., edited by: J. T. Houghton, Ding, Y., and Griggs, D. J.:  
41 Atmospheric Chemistry and Greenhouse Gases, in *Climate Change 2001: The*  
42 *Scientific Basis*, Cambridge University Press, Cambridge, UK, pp. 239–287, 2001.

43 Previdi, M., and Polvani, L. M.: Climate system response to stratospheric ozone  
44 depletion and recovery, *Quart. J. Roy. Meteor. Soc.*, 140, 2401–2419,  
45 10.1002/qj.2330, 2014.

1 Ramaswamy, V., Schwarzkopf, M. D., Randel, W. J., Santer, B. D., Soden, B. J., and  
2 Stenchikov, G. L.: Anthropogenic and Natural Influences in the Evolution of Lower  
3 Stratospheric Cooling, *Science*, 311, 1138-1141, 10.1126/science.1122587, 2006.

4 Randel, W. J., and Wu, F.: Cooling of the Arctic and Antarctic Polar Stratospheres  
5 due to Ozone Depletion, *J. Clim.*, 12, 1467-1479, 10.1175/1520-  
6 0442(1999)012<1467:COTAAA>2.0.CO;2, 1999.

7 Randel, W. J., Park, M., Wu, F., and Livesey, N.: A Large Annual Cycle in Ozone  
8 above the Tropical Tropopause Linked to the Brewer–Dobson Circulation, *J. Atmos.*  
9 *Sci.*, 64, 4479-4488, 10.1175/2007JAS2409.1, 2007.

10 Randel, W. J., Shine, K. P., Austin, J., Barnett, J., Claud, C., Gillett, N. P., Keckhut,  
11 P., Langematz, U., Lin, R., Long, C., Mears, C., Miller, A., Nash, J., Seidel, D. J.,  
12 Thompson, D. W. J., Wu, F., and Yoden, S.: An update of observed stratospheric  
13 temperature trends, *J. Geophys. Res.*, 114, D02107, 10.1029/2008JD010421, 2009.

14 Randeniya, L. K., Vohralik, P. F., and Plumb, I. C.: Stratospheric ozone depletion at  
15 northern mid latitudes in the 21st century: The importance of future concentrations of  
16 greenhouse gases nitrous oxide and methane, *Geophys. Res. Lett.*, 29, 10-11-10-14,  
17 10.1029/2001GL014295, 2002.

18 Ravishankara, A. R., Daniel, J. S., and Portmann, R. W.: Nitrous Oxide (N<sub>2</sub>O): The  
19 Dominant Ozone-Depleting Substance Emitted in the 21st Century, *Science*, 326,  
20 123-125, 10.1126/science.1176985, 2009.

21 Reader, M. C., Plummer, D. A., Scinocca, J. F., and Shepherd, T. G.: Contributions to  
22 twentieth century total column ozone change from halocarbons, tropospheric ozone  
23 precursors, and climate change, *Geophys. Res. Lett.*, 40, 6276-6281,  
24 10.1002/2013GL057776, 2013.

25 Revell, L. E., Bodeker, G. E., Smale, D., Lehmann, R., Huck, P. E., Williamson, B.  
26 E., Rozanov, E., and Struthers, H.: The effectiveness of N<sub>2</sub>O in depleting  
27 stratospheric ozone, *Geophys. Res. Lett.*, 39, L15806, 10.1029/2012GL052143, 2012.

28 Rosenfield, J. E., Douglass, A. R., and Considine, D. B.: The impact of increasing  
29 carbon dioxide on ozone recovery, *J. Geophys. Res.*, 107, ACH 7-1-ACH 7-9,  
30 10.1029/2001JD000824, 2002.

31 Santer, B. D., Wigley, T. M. L., Boyle, J. S., Gaffen, D. J., Hnilo, J. J., Nychka, D.,  
32 Parker, D. E., and Taylor, K. E.: Statistical significance of trends and trend  
33 differences in layer-average atmospheric temperature time series, *J. Geophys. Res.*,  
34 105, 7337-7356, 10.1029/1999JD901105, 2000.

35 Santer, B. D., Sausen, R., Wigley, T. M. L., Boyle, J. S., AchutaRao, K., Doutriaux,  
36 C., Hansen, J. E., Meehl, G. A., Roeckner, E., Ruedy, R., Schmidt, G., and Taylor, K.  
37 E.: Behavior of tropopause height and atmospheric temperature in models, reanalyses,  
38 and observations: Decadal changes, *J. Geophys. Res.*, 108, 4002,  
39 10.1029/2002JD002258, 2003a.

40 Santer, B. D., Wehner, M. F., Wigley, T. M. L., Sausen, R., Meehl, G. A., Taylor, K.  
41 E., Ammann, C., Arblaster, J., Washington, W. M., Boyle, J. S., and Brüggemann,  
42 W.: Contributions of Anthropogenic and Natural Forcing to Recent Tropopause  
43 Height Changes, *Science*, 301, 479-483, 10.1126/science.1084123, 2003b.

44 Schmidt, G. A., Ruedy, R., Hansen, J. E., Aleinov, I., Bell, N., Bauer, M., Bauer, S.,  
45 Cairns, B., Canuto, V., Cheng, Y., Del Genio, A., Faluvegi, G., Friend, A. D., Hall, T.

1 M., Hu, Y., Kelley, M., Kiang, N. Y., Koch, D., Lacis, A. A., Lerner, J., Lo, K. K.,  
2 Miller, R. L., Nazarenko, L., Oinas, V., Perlwitz, J., Perlwitz, J., Rind, D., Romanou,  
3 A., Russell, G. L., Sato, M., Shindell, D. T., Stone, P. H., Sun, S., Tausnev, N.,  
4 Thresher, D., and Yao, M.-S.: Present-Day Atmospheric Simulations Using GISS  
5 ModelE: Comparison to In Situ, Satellite, and Reanalysis Data, *J. Clim.*, 19, 153-192,  
6 10.1175/JCLI3612.1, 2006.

7 Scinocca, J. F., McFarlane, N. A., Lazare, M., Li, J., and Plummer, D.: Technical  
8 Note: The CCCma third generation AGCM and its extension into the middle  
9 atmosphere, *Atmos. Chem. Phys.*, 8, 7055-7074, 10.5194/acp-8-7055-2008, 2008.

10 Sexton, D. M. H.: The effect of stratospheric ozone depletion on the phase of the  
11 Antarctic Oscillation, *Geophys. Res. Lett.*, 28, 3697-3700, 10.1029/2001GL013376,  
12 2001.

13 Shepherd, T. G.: Dynamics, stratospheric ozone, and climate change, *Atmos.-Ocean*,  
14 46, 117-138, doi:10.3137/ao.460106, 2008.

15 Shepherd, T. G., Plummer, D. A., Scinocca, J. F., Hegglin, M. I., Fioletov, V. E.,  
16 Reader, M. C., Remsberg, E., von Clarmann, T., and Wang, H. J.: Reconciliation of  
17 halogen-induced ozone loss with the total-column ozone record, *Nature Geosci.*, 7,  
18 443-449, 10.1038/ngeo2155, 2014.

19 Sherwood, S. C., Meyer, C. L., Allen, R. J., and Titchner, H. A.: Robust Tropospheric  
20 Warming Revealed by Iteratively Homogenized Radiosonde Data, *J. Clim.*, 21, 5336-  
21 5352, 10.1175/2008JCLI2320.1, 2008.

22 Shindell, D. T., and Schmidt, G. A.: Southern Hemisphere climate response to ozone  
23 changes and greenhouse gas increases, *Geophys. Res. Lett.*, 31, L18209,  
24 10.1029/2004GL020724, 2004.

25 Shindell, D. T., Faluvegi, G., Stevenson, D. S., Krol, M. C., Emmons, L. K.,  
26 Lamarque, J. F., Pétron, G., Dentener, F. J., Ellingsen, K., Schultz, M. G., Wild, O.,  
27 Amann, M., Atherton, C. S., Bergmann, D. J., Bey, I., Butler, T., Cofala, J., Collins,  
28 W. J., Derwent, R. G., Doherty, R. M., Drevet, J., Eskes, H. J., Fiore, A. M., Gauss,  
29 M., Hauglustaine, D. A., Horowitz, L. W., Isaksen, I. S. A., Lawrence, M. G.,  
30 Montanaro, V., Müller, J. F., Pitari, G., Prather, M. J., Pyle, J. A., Rast, S., Rodriguez,  
31 J. M., Sanderson, M. G., Savage, N. H., Strahan, S. E., Sudo, K., Szopa, S., Unger,  
32 N., van Noije, T. P. C., and Zeng, G.: Multimodel simulations of carbon monoxide:  
33 Comparison with observations and projected near-future changes, *J. Geophys. Res.*,  
34 111, D19306, 10.1029/2006JD007100, 2006.

35 Shindell, D. T., Lamarque, J. F., Schulz, M., Flanner, M., Jiao, C., Chin, M., Young,  
36 P. J., Lee, Y. H., Rotstayn, L., Mahowald, N., Milly, G., Faluvegi, G., Balkanski, Y.,  
37 Collins, W. J., Conley, A. J., Dalsören, S., Easter, R., Ghan, S., Horowitz, L., Liu, X.,  
38 Myhre, G., Nagashima, T., Naik, V., Rumbold, S. T., Skeie, R., Sudo, K., Szopa, S.,  
39 Takemura, T., Voulgarakis, A., Yoon, J. H., and Lo, F.: Radiative forcing in the  
40 ACCMIP historical and future climate simulations, *Atmos. Chem. Phys.*, 13, 2939-  
41 2974, 10.5194/acp-13-2939-2013, 2013a.

42 Shindell, D. T., Pechony, O., Voulgarakis, A., Faluvegi, G., Nazarenko, L.,  
43 Lamarque, J. F., Bowman, K., Milly, G., Kovari, B., Ruedy, R., and Schmidt, G. A.:  
44 Interactive ozone and methane chemistry in GISS-E2 historical and future climate  
45 simulations, *Atmos. Chem. Phys.*, 13, 2653-2689, 10.5194/acp-13-2653-2013, 2013b.

1 Solomon, S., Young, P. J., and Hassler, B.: Uncertainties in the evolution of  
2 stratospheric ozone and implications for recent temperature changes in the tropical  
3 lower stratosphere, *Geophys. Res. Lett.*, 39, L17706, 10.1029/2012gl052723, 2012.

4 Son, S.-W., Tandon, N. F., Polvani, L. M., and Waugh, D. W.: Ozone hole and  
5 Southern Hemisphere climate change, *Geophys. Res. Lett.*, 36, L15705,  
6 10.1029/2009GL038671, 2009.

7 Son, S. W., Polvani, L. M., Waugh, D. W., Akiyoshi, H., Garcia, R., Kinnison, D.,  
8 Pawson, S., Rozanov, E., Shepherd, T. G., and Shibata, K.: The Impact of  
9 Stratospheric Ozone Recovery on the Southern Hemisphere Westerly Jet, *Science*,  
10 320, 1486-1489, 10.1126/science.1155939, 2008.

11 Son, S. W., Gerber, E. P., Perlwitz, J., Polvani, L. M., Gillett, N. P., Seo, K. H.,  
12 Eyring, V., Shepherd, T. G., Waugh, D., Akiyoshi, H., Austin, J., Baumgaertner, A.,  
13 Bekki, S., Braesicke, P., Brühl, C., Butchart, N., Chipperfield, M. P., Cugnet, D.,  
14 Dameris, M., Dhomse, S., Frith, S., Garny, H., Garcia, R., Hardiman, S. C., Jöckel, P.,  
15 Lamarque, J. F., Mancini, E., Marchand, M., Michou, M., Nakamura, T.,  
16 Morgenstern, O., Pitari, G., Plummer, D. A., Pyle, J., Rozanov, E., Scinocca, J. F.,  
17 Shibata, K., Smale, D., Teyssède, H., Tian, W., and Yamashita, Y.: Impact of  
18 stratospheric ozone on Southern Hemisphere circulation change: A multimodel  
19 assessment, *J. Geophys. Res.*, 115, D00M07, 10.1029/2010JD014271, 2010.

20 SPARC CCMVal, SPARC CCMVal Report on the Evaluation of Chemistry-Climate  
21 Models, edited by: Eyring, V., Shepherd, T. G., Waugh, D. W., SPARC Report No. 5,  
22 WCRP-132, WMO/TD-No. 1526, 2010.

23 Stevenson, D. S., Dentener, F. J., Schultz, M. G., Ellingsen, K., van Noije, T. P. C.,  
24 Wild, O., Zeng, G., Amann, M., Atherton, C. S., Bell, N., Bergmann, D. J., Bey, I.,  
25 Butler, T., Cofala, J., Collins, W. J., Derwent, R. G., Doherty, R. M., Drevet, J.,  
26 Eskes, H. J., Fiore, A. M., Gauss, M., Hauglustaine, D. A., Horowitz, L. W., Isaksen,  
27 I. S. A., Krol, M. C., Lamarque, J. F., Lawrence, M. G., Montanaro, V., Müller, J. F.,  
28 Pitari, G., Prather, M. J., Pyle, J. A., Rast, S., Rodriguez, J. M., Sanderson, M. G.,  
29 Savage, N. H., Shindell, D. T., Strahan, S. E., Sudo, K., and Szopa, S.: Multimodel  
30 ensemble simulations of present-day and near-future tropospheric ozone, *J. Geophys.*  
31 *Res.*, 111, D08301, 10.1029/2005JD006338, 2006.

32 Stevenson, D. S., Young, P. J., Naik, V., Lamarque, J. F., Shindell, D. T.,  
33 Voulgarakis, A., Skeie, R. B., Dalsoren, S. B., Myhre, G., Berntsen, T. K., Folberth,  
34 G. A., Rumbold, S. T., Collins, W. J., MacKenzie, I. A., Doherty, R. M., Zeng, G.,  
35 van Noije, T. P. C., Strunk, A., Bergmann, D., Cameron-Smith, P., Plummer, D. A.,  
36 Strode, S. A., Horowitz, L., Lee, Y. H., Szopa, S., Sudo, K., Nagashima, T., Josse, B.,  
37 Cionni, I., Righi, M., Eyring, V., Conley, A., Bowman, K. W., Wild, O., and  
38 Archibald, A.: Tropospheric ozone changes, radiative forcing and attribution to  
39 emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project  
40 (ACCMIP), *Atmos. Chem. Phys.*, 13, 3063-3085, 10.5194/acp-13-3063-2013, 2013.

41 Stevenson, D. S.: Atmospheric chemistry: Climate's chemical sensitivity, *Nature*  
42 *Clim. Change*, 5, 21-22, 10.1038/nclimate2477, 2015.

43 Stiller, G. P., von Clarmann, T., Haenel, F., Funke, B., Glatthor, N., Grabowski, U.,  
44 Kellmann, S., Kiefer, M., Linden, A., Lossow, S., and López-Puertas, M.: Observed  
45 temporal evolution of global mean age of stratospheric air for the 2002 to 2010  
46 period, *Atmos. Chem. Phys.*, 12, 3311-3331, 10.5194/acp-12-3311-2012, 2012.

1 Struthers, H., Bodeker, G. E., Austin, J., Bekki, S., Cionni, I., Dameris, M., Giorgetta,  
2 M. A., Grewe, V., Lefèvre, F., Lott, F., Manzini, E., Peter, T., Rozanov, E., and  
3 Schraner, M.: The simulation of the Antarctic ozone hole by chemistry-climate  
4 models, *Atmos. Chem. Phys.*, 9, 6363-6376, 10.5194/acp-9-6363-2009, 2009.

5 Sudo, K., Takahashi, M., and Akimoto, H.: Future changes in stratosphere-  
6 troposphere exchange and their impacts on future tropospheric ozone simulations,  
7 *Geophys. Res. Lett.*, 30, 2256, 10.1029/2003GL018526, 2003.

8 Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the  
9 Experiment Design, *Bull. Am. Meteorol. Soc.*, 93, doi:10.1175/BAMS-D-11-00094.1,  
10 2012.

11 Thompson, D. W. J., and Wallace, J. M.: Annular Modes in the Extratropical  
12 Circulation. Part I: Month-to-Month Variability\*, *J. Clim.*, 13, 1000-1016,  
13 10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2, 2000.

14 Thompson, D. W. J., and Solomon, S.: Interpretation of Recent Southern Hemisphere  
15 Climate Change, *Science*, 296, 895-899, 10.1126/science.1069270, 2002.

16 Thompson, D. W. J., Solomon, S., Kushner, P. J., England, M. H., Grise, K. M., and  
17 Karoly, D. J.: Signatures of the Antarctic ozone hole in Southern Hemisphere surface  
18 climate change, *Nature Geosci.*, 4, 741-749, doi:10.1038/ngeo1296, 2011.

19 Thorne, P. W., Parker, D. E., Tett, S. F. B., Jones, P. D., McCarthy, M., Coleman, H.,  
20 and Brohan, P.: Revisiting radiosonde upper air temperatures from 1958 to 2002, *J.*  
21 *Geophys. Res.*, 110, D18105, 10.1029/2004JD005753, 2005.

22 UNEP: Environmental effects of ozone depletion and its interaction with climate  
23 change: 2015 assessment, United Nations Environment Programme (UNEP), Nairobi,  
24 2015.

25 van Vuuren, Detlef, P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard,  
26 K., Hurtt, G., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M.,  
27 Nakicenovic, N., Smith, S., and Rose, S.: The representative concentration pathways:  
28 an overview, *Clim. Change*, 109, 5-31, 10.1007/s10584-011-0148-z, 2011.

29 Voulgarakis, A., Naik, V., Lamarque, J. F., Shindell, D. T., Young, P. J., Prather, M.  
30 J., Wild, O., Field, R. D., Bergmann, D., Cameron-Smith, P., Cionni, I., Collins, W.  
31 J., Dalsören, S. B., Doherty, R. M., Eyring, V., Faluvegi, G., Folberth, G. A.,  
32 Horowitz, L. W., Josse, B., MacKenzie, I. A., Nagashima, T., Plummer, D. A., Righi,  
33 M., Rumbold, S. T., Stevenson, D. S., Strode, S. A., Sudo, K., Szopa, S., and Zeng,  
34 G.: Analysis of present day and future OH and methane lifetime in the ACCMIP  
35 simulations, *Atmos. Chem. Phys.*, 13, 2563-2587, 10.5194/acp-13-2563-2013, 2013.

36 Watanabe, S., Hajima, T., Sudo, K., Nagashima, T., Takemura, T., Okajima, H.,  
37 Nozawa, T., Kawase, H., Abe, M., Yokohata, T., Ise, T., Sato, H., Kato, E., Takata,  
38 K., Emori, S., and Kawamiya, M.: MIROC-ESM 2010: model description and basic  
39 results of CMIP5-20c3m experiments, *Geosci. Model Dev.*, 4, 845-872, 10.5194/gmd-  
40 4-845-2011, 2011.

41 Waugh, D. W., Oman, L., Kawa, S. R., Stolarski, R. S., Pawson, S., Douglass, A. R.,  
42 Newman, P. A., and Nielsen, J. E.: Impacts of climate change on stratospheric ozone  
43 recovery, *Geophys. Res. Lett.*, 36, L03805, 10.1029/2008GL036223, 2009a.

44 Waugh, D. W., Oman, L., Newman, P. A., Stolarski, R. S., Pawson, S., Nielsen, J. E.,  
45 and Perlwitz, J.: Effect of zonal asymmetries in stratospheric ozone on simulated

1 Southern Hemisphere climate trends, *Geophys. Res. Lett.*, 36, L18701,  
2 10.1029/2009GL040419, 2009b.

3 Wilcox, L. J., Charlton-Perez, A. J., and Gray, L. J.: Trends in Austral jet position in  
4 ensembles of high- and low-top CMIP5 models, *J. Geophys. Res.*, 117, D13115,  
5 10.1029/2012JD017597, 2012.

6 Wild, O.: Modelling the global tropospheric ozone budget: exploring the variability in  
7 current models, *Atmos. Chem. Phys.*, 7, 2643-2660, 10.5194/acp-7-2643-2007, 2007.

8 WMO: Scientific Assessment of Ozone Depletion: 2006, World Meteorological  
9 Organization, Geneva, Switzerland, 572pp., 2007.

10 WMO: Scientific Assessment of Ozone Depletion: 2010, World Meteorological  
11 Organization, Geneva, Switzerland, 516 pp., 2011.

12 WMO: Scientific Assessment of Ozone Depletion: 2014, World Meteorological  
13 Organization, Global Ozone Research and Monitoring Project, Geneva, Switzerland,  
14 2014.

15 Young, P. J., Rosenlof, K. H., Solomon, S., Sherwood, S. C., Fu, Q., and Lamarque, J.  
16 F.: Changes in Stratospheric Temperatures and Their Implications for Changes in the  
17 Brewer-Dobson Circulation, 1979-2005, *J. Clim.*, 25, 1759-1772,  
18 10.1175/2011jcli4048.1, 2011.

19 Young, P. J., Archibald, A. T., Bowman, K. W., Lamarque, J. F., Naik, V., Stevenson,  
20 D. S., Tilmes, S., Voulgarakis, A., Wild, O., Bergmann, D., Cameron-Smith, P.,  
21 Cionni, I., Collins, W. J., Dalsoren, S. B., Doherty, R. M., Eyring, V., Faluvegi, G.,  
22 Horowitz, L. W., Josse, B., Lee, Y. H., MacKenzie, I. A., Nagashima, T., Plummer,  
23 D. A., Righi, M., Rumbold, S. T., Skeie, R. B., Shindell, D. T., Strode, S. A., Sudo,  
24 K., Szopa, S., and Zeng, G.: Pre-industrial to end 21st century projections of  
25 tropospheric ozone from the Atmospheric Chemistry and Climate Model  
26 Intercomparison Project (ACCMIP), *Atmos. Chem. Phys.*, 13, 2063-2090,  
27 10.5194/acp-13-2063-2013, 2013a.

28 Young, P. J., Butler, A. H., Calvo, N., Haimberger, L., Kushner, P. J., Marsh, D. R.,  
29 Randel, W. J., and Rosenlof, K. H.: Agreement in late twentieth century Southern  
30 Hemisphere stratospheric temperature trends in observations and CCMVal-2, CMIP3,  
31 and CMIP5 models, *J. Geophys. Res.*, 118, 605-613, 10.1002/jgrd.50126, 2013b.

32 Young, P. J., Davis, S. M., Hassler, B., Solomon, S., and Rosenlof, K. H.: Modeling  
33 the climate impact of Southern Hemisphere ozone depletion: The importance of the  
34 ozone data set, *Geophys. Res. Lett.*, 41(24), 9033-9039, doi:10.1002/2014GL061738,  
35 2014.

36 Zeng, G., and Pyle, J. A.: Changes in tropospheric ozone between 2000 and 2100  
37 modeled in a chemistry-climate model, *Geophys. Res. Lett.*, 30, 1392,  
38 10.1029/2002GL016708, 2003.

39 Zeng, G., Pyle, J. A., and Young, P. J.: Impact of climate change on tropospheric  
40 ozone and its global budgets, *Atmos. Chem. Phys.*, 8, 369-387, 10.5194/acp-8-369-  
41 2008, 2008.

42 Zeng, G., Morgenstern, O., Braesicke, P., and Pyle, J. A.: Impact of stratospheric  
43 ozone recovery on tropospheric ozone and its budget, *Geophys. Res. Lett.*, 37,  
44 L09805, 10.1029/2010GL042812, 2010.

1 Zou, C.-Z., Goldberg, M. D., Cheng, Z., Grody, N. C., Sullivan, J. T., Cao, C., and  
2 Tarpley, D.: Recalibration of microwave sounding unit for climate studies using  
3 simultaneous nadir overpasses, *J. Geophys. Res.*, 111, D19114,  
4 10.1029/2005JD006798, 2006.

5 Zou, C.-Z., Gao, M., and Goldberg, M. D.: Error Structure and Atmospheric  
6 Temperature Trends in Observations from the Microwave Sounding Unit, *J. Clim.*,  
7 22, 1661-1681, 10.1175/2008JCLI2233.1, 2009.

8

9

1 Table 1 Summary of the ACCMIP models used here

Model	Stratospheric ozone	Composition-radiation coupling	Photolysis scheme	Reference
CESM-CAM-superfast	CHEM	Yes	Adjusted look-up table	Lamarque et al. (2012)
CMAM	CHEM	Yes	Adjusted look-up table	Scinocca et al. (2008)
GFDL-AM3	CHEM	Yes	Adjusted look-up table	Donner et al. (2011); Naik et al. (2013a)
GISS-E2-R	CHEM	Yes	Online	Koch et al. (2006); Shindell et al. (2013b)
HadGEM2	NOCHEM	Yes	Look-up table + TCO overhead	Collins et al. (2011)
MIROC-CHEM	CHEM	Yes	Online	Watanabe et al. (2011)
NCAR-CAM3.5	CHEM	Yes	Adjusted look-up table	Lamarque et al. (2011; 2012)
UM-CAM	NOCHEM	No	Look-up table	Zeng et al. (2008; 2010)

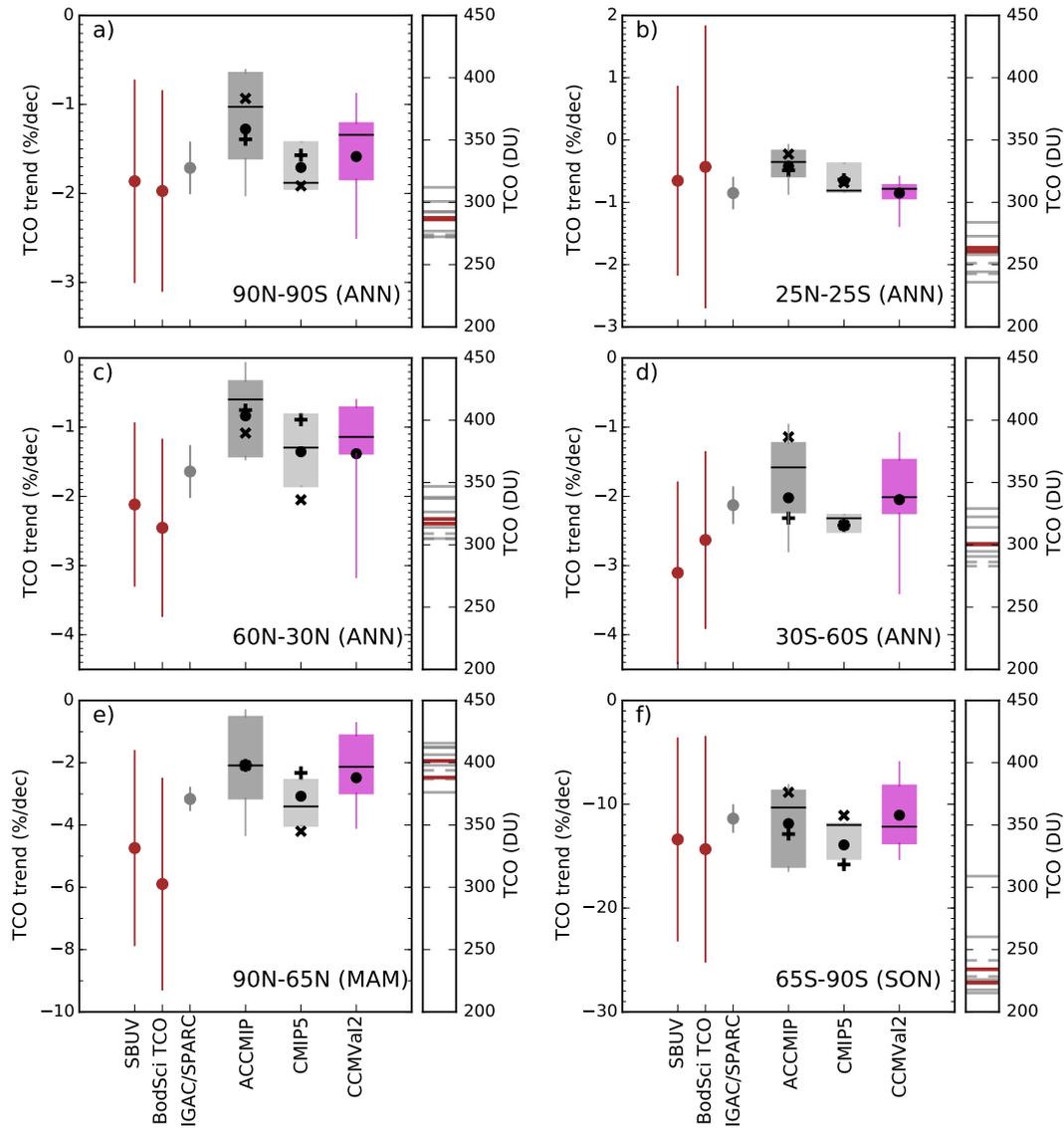
2  
3

1 **Table 2 Global annual mean of TCO (DU)**

Scenario	Year	ACCMIP*	CMIP5*	IGAC/SPARC
Hist	1850	294±16	300±19	293±1
	1980	300±19	306±20	292±2
	2000	291±16	297±20	281±1
RCP2.6	2030	295±16	301±20	288±1
	2100	297±18	302±20	294±0
RCP8.5	2030	300±17	306±20	290±1
	2100	316±23	323±11	304±0

2  
3

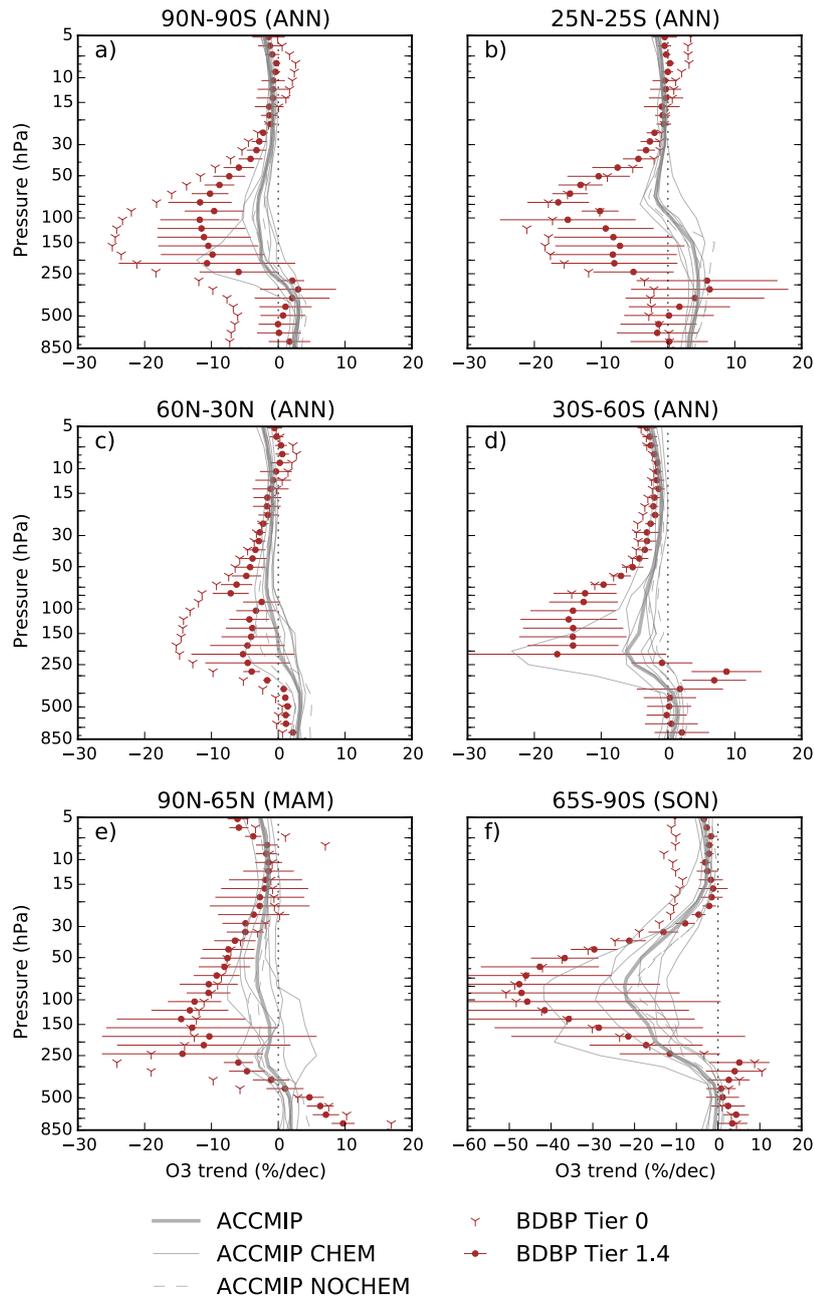
\*For the historical period and the RCPs emission scenarios considered here as calculated from the CHEM models and the IGAC/SPARC data set (see Section 2). The multi-model mean is given along with uncertainties ( $\pm 1$  standard deviation).



— SBUV / BodSci TCO    — ACCMIP CHEM    - - ACCMIP NOCHEM

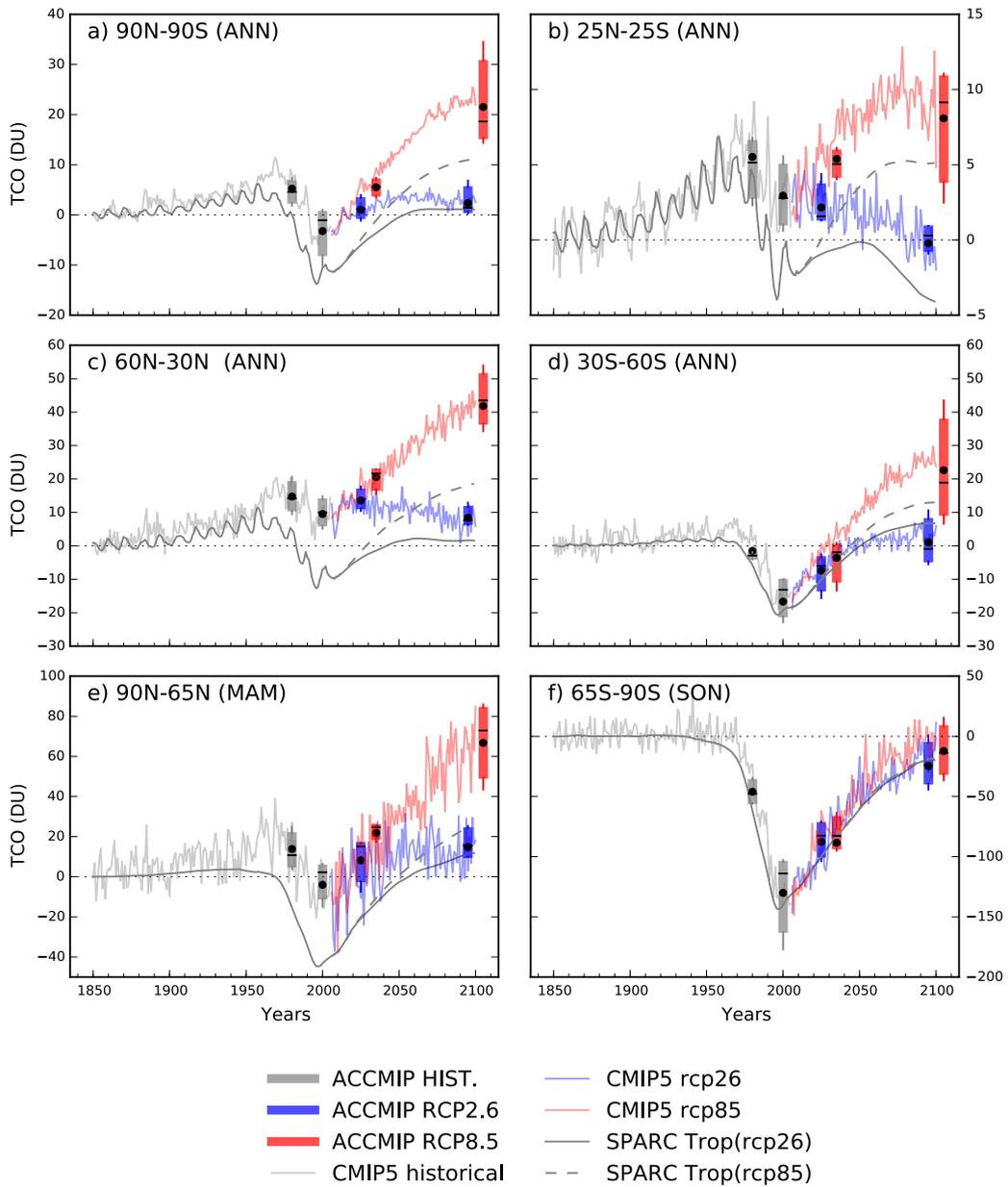
1

2 Figure 1. Total column ozone trends from 1980 to 2000 ( $\% \text{ dec}^{-1}$ ) for the annual mean  
 3 (ANN) (a) global, (b) in the tropics, (c) in the northern midlatitudes, (d) in the  
 4 southern midlatitudes, (e) for the boreal spring in the Arctic (MAM), and (f) for  
 5 austral spring in the Antarctic (SON). The box, whiskers and line indicate the  
 6 interquartile range, 95 % range and median respectively, for the ACCMIP (light  
 7 grey), CMIP5 (dark grey) and CCMVal2 (magenta) models. Multi-model means are  
 8 indicated by dots. CHEM (models with interactive chemistry) and NOCHEM (models  
 9 that prescribe ozone) means are indicated by ‘plus’ and ‘cross’ symbols, respectively.  
 10 Observations and IGAC/SPARC data sets are represented by error bars indicating the  
 11 95 % confidence intervals (one tail).



1

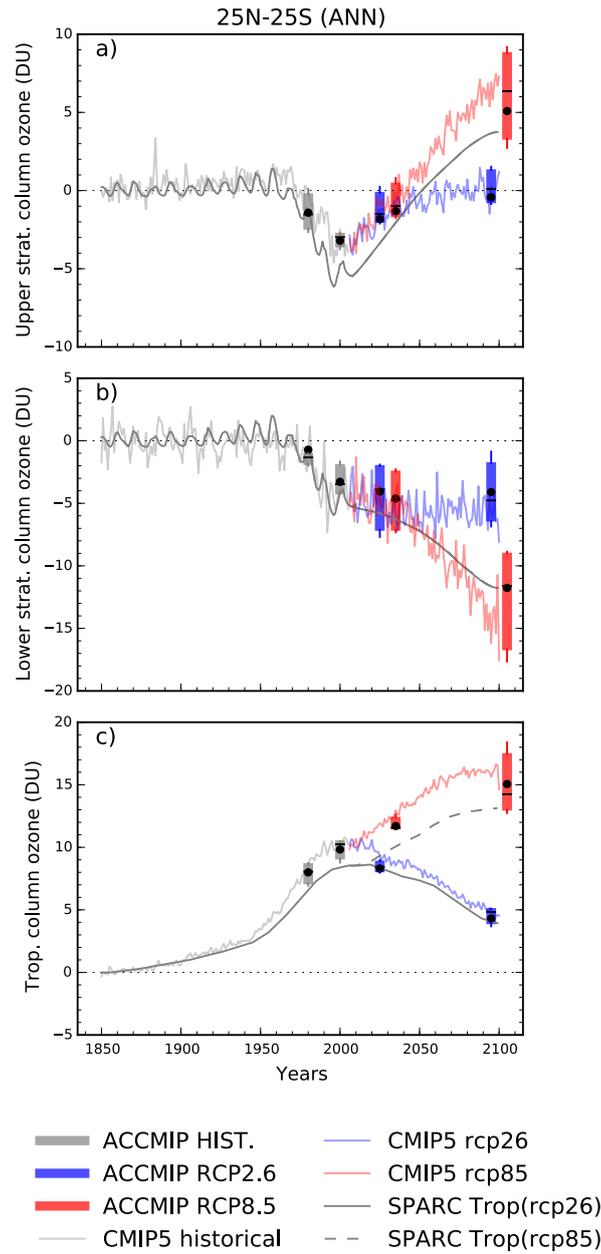
2 Figure 2. Vertically resolved ozone trends (% dec<sup>-1</sup>), for ACCMIP multi-model mean,  
 3 CHEM and NOCHEM models compared to BDBP Tier 1.4 (regression model fit with  
 4 uncertainty estimates indicating 95 % confidence intervals, one tail) and Tier 0  
 5 (observations).



1

2 Figure 3. Total column ozone (DU) time series from 1850 to 2100. The box, whiskers  
 3 and line indicate the interquartile range, 95 % range and median respectively, for the  
 4 ACCMIP CHEM models. In addition, the multi-model mean of the CMIP5 CHEM  
 5 models and the IGAC/SPARC mean are shown. All data sets are normalised to Hist  
 6 1850 time slice levels.

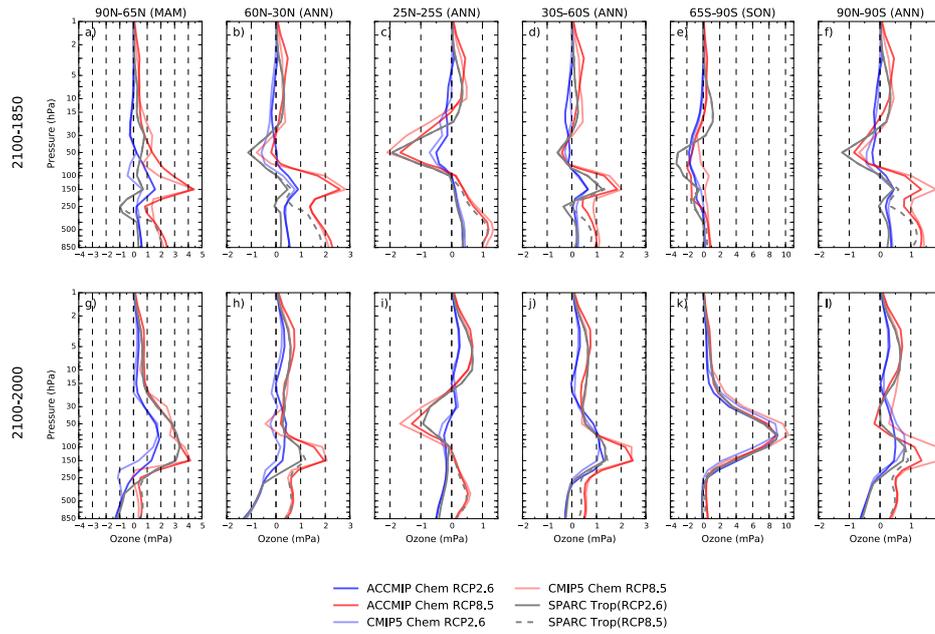
7



1

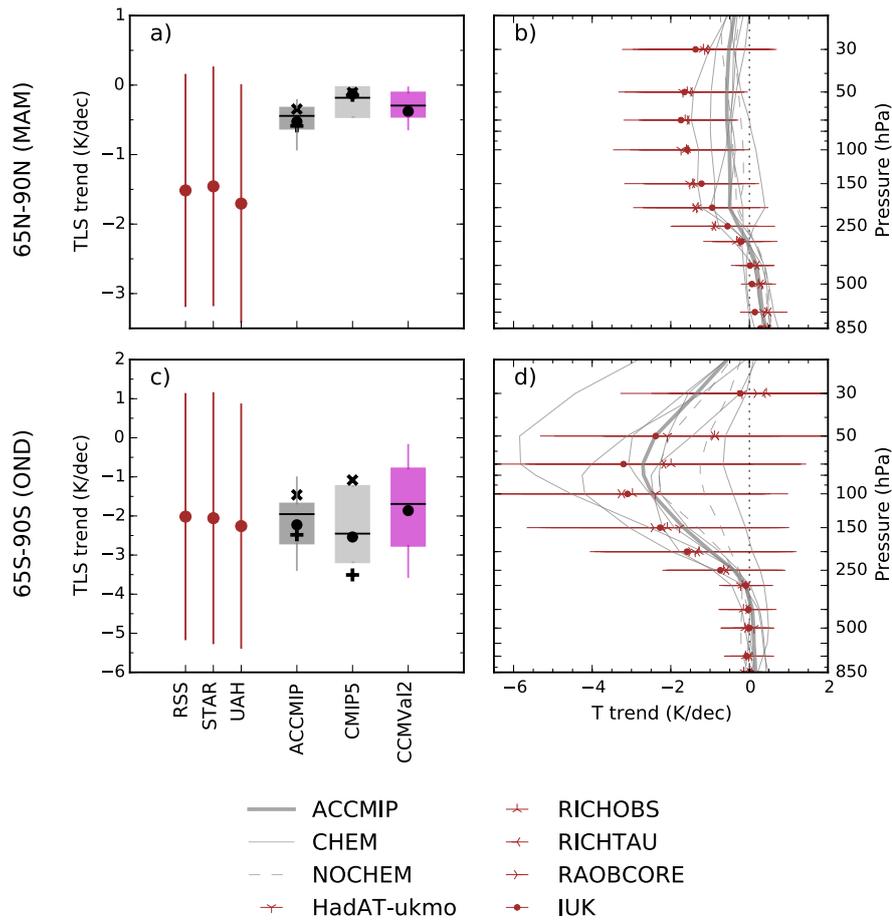
2 Figure 4. As Fig. 3, but for the upper stratosphere (10–1 hPa), lower stratosphere (>15  
 3 hPa) and tropospheric columns ozone (DU) in the tropics.

4



1  
2  
3  
4  
5  
6  
7

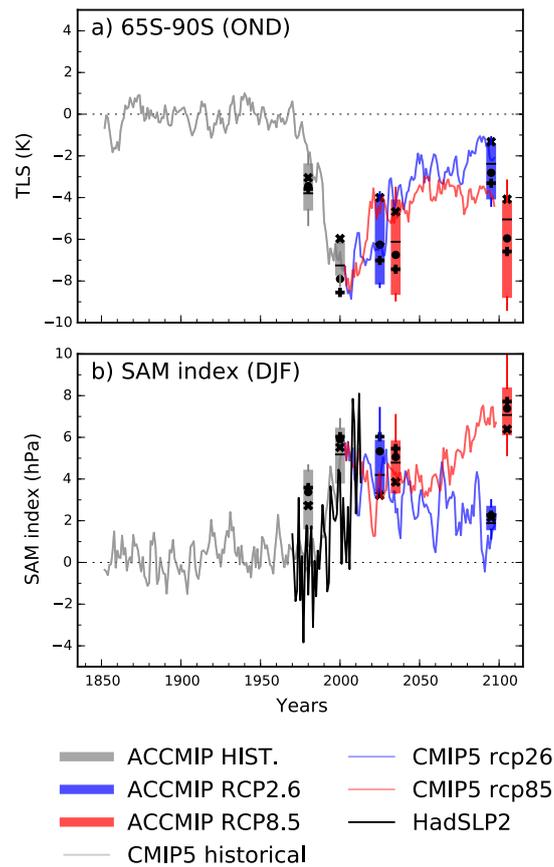
Figure 5. Vertically resolved ozone change between 2100 and 1850 (a to f), and 2100 and 2000 (g to l) time slices. Figures a-g are for Arctic boreal spring mean, b-h and d-j for NH and SH midlatitudes annual mean respectively, c-i for tropical annual mean, e-k for Antarctic austral spring mean, and f-l for global annual mean.



1

2 Figure 6. Temperature trends from 1980 to 2000 ( $K\ dec^{-1}$ ). Figures (a) and (c)  
 3 represent MSU temperature lower stratosphere (TLS) for boreal spring in the Arctic  
 4 (MAM) and for austral spring in the Antarctic (OND). The box, whiskers, line, dot,  
 5 'plus' and 'cross' symbols show the interquartile range, 95 % range, median, multi-  
 6 model mean, CHEM and NOCHEM means respectively, for the ACCMIP (light  
 7 grey), CMIP5 (dark grey) and CCMVal2 (magenta) models. Figures (b) and (d)  
 8 represent vertically resolved temperature (T) trends for the ACCMIP simulations  
 9 (light grey). Observational data sets are represented by error bars indicating the 95 %  
 10 confidence intervals (one tail).

11



1

2 Figure 7. (a) MSU temperature lower stratosphere (TLS) and (b) SAM index time  
 3 series from 1850 to 2100. The box, whiskers, line, dot, 'plus' and 'cross' symbols  
 4 show the interquartile range, 95 % range, median, multi-model mean, CHEM and  
 5 NOCHEM means respectively, for the ACCMIP models. The five years average of  
 6 the CMIP5 multi-model mean is shown. In addition, HadSLP2 observational data set  
 7 for (b) is represented by a solid black line. The ACCMIP models are normalised to  
 8 Hist 1850 time slice levels, and the HadSLP2 data set and CMIP5 models are relative  
 9 to 1860–1899 climatology.